[COMMITTEE PRINT]

REPORTS SUBMITTED TO CONGRESS BY NASA PURSUANT TO HOUSE REPORT 98-65, TO ACCOMPANY H.R. 2065, THE NASA AUTHORIZATION ACT FOR FISCAL YEAR 1984

REPORT

PREPARED BY THE

SUBCOMMITTEE ON
SPACE SCIENCE AND APPLICATIONS

TRANSMITTED TO THE

COMMITTEE ON
SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
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LETTER OF SUBMITTAL

House of Representatives,
Committee on Science and Technology,
Washington, DC, December 31, 1984.

Hon. Don Fuqua,
Chairman, Committee on Science and Technology,
U.S. House of Representatives.

Dear Mr. Chairman: This report contains a compilation of various reports submitted to Congress by NASA during the 98th Congress. These reports are responsive to the Committee's requests as iterated in House Report 98-65, report to accompany H.R. 2065, the NASA Authorization Act for Fiscal Year 1984.

Brief explanations of the reports requests follow the table of contents section herein. I commend these reports to your attention.

Sincerely,

Harold L. Volkmer,
Chairman, Subcommittee on Space Science and Applications.

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EXPLANATION OF REPORTS

Pursuant to House Report 98-65 to accompany H.R. 2065, the NASA authorization bill for fiscal year 1984, the Committee on Science and Technologv requested that NASA submit the following reports, summaries, plans, etc., to the Congress or committee.

A plan for maintenance of expendable launch vehicle capability in support of the new space transportation system 01

This report is the result of a request made by the Committee on Science and Technology that NASA submit by September 1, 1983, a plan for maintenance of expendable launch vehicle capability in support of the new space transportation system. The plan was requested to include appropriate recommendations to allow U.S. expendable launch vehicles to be competitive with foreign launch vehicles and recommendations to facilitate commercial ventures.

The space transportation system marketing plan 10

This report is the result of a request made by the Committee that NASA shall communicate to the Congress by October 1, 1983, both short- and long-term plans to establish an effective private sector space shuttle payload marketing activity.

Research and technology for solar system exploration missions 22

This report responds to a committee request that NASA report on the status of long-term plans for technology development (including power sources) for deep space missions beyond Galileo and ISPM.

Report of the ad hoc Subcommittee on Space Research and Technology for Future Planetary Missions 34

Along with its request for a report on NASA's solar system exploration missions, the committee further requested that NASA instruct its NASA Advisory Council to initiate a review of the adequacy of current Space Research and Technology programs for supporting future planetary missions, and report the results of that review to the committee.

Microgravity science and applications annual report to the House Committee on Science and Technology 59

The committee requested that NASA submit to the Congress in December 1983 and every year thereafter, a comprehensive annual report on its Materials Processing in Space Program. In the committee's view, the realization of the full potential for materials processing in space would be accelerated by better program focus and direction. The report was requested to outline program objectives and direction and include research and applied science goals, milestones, status reports, budget information, and information concerning commercial, interagency and international involvement.

Alternatives for conducting NASA's Aeronautical Research and Technology Program (October 20, 1983) 80

This letter responds to a committee request that the NASA Administrator examine alternatives for conducting aeronautical research and technology programs with a view toward increasing the number of aeronautical research personnel by 220.

40x80 wind tunnel accident investigation 82

The committee requested the NASA Administrator to prepare a report which describes what steps are being taken to avoid future structural facility failures. The report was requested to describe the organization, communication, and management tools to be used.

"Civil Applications of Nuclear Power," final report of the Civil Missions Advisory Group (August 1984) 96

This report was responsive to the committee's understanding that space nuclear reactor technology will have both civilian and defense applications and that the technology base resulting from the presently existing agreement among NASA, DOE, and DARPA will provide the foundation for designing space power subsystems suitable for future, as yet unauthorized, NASA missions. To ensure that such mission definition analyses would proceed in a deliberate and timely manner, NASA was instructed to establish a mission planning and definition activity as part of the SP-100 Program management plan, and to present evidence to the committee that the organizational arrangements for implementing such activity are in place. The committee also requested an interim report which is reprinted herein, following the final report.

"Civil Applications Of Nuclear Power"—interim report of the Civil Missions Advisory Group (July 26, 1983) 208

The committee requested that each year NASA provide a summary report to the committee concurrently with the submission of the President's annual budget to the Congress that details plans, accomplishments, schedules, and long range budgetary projections related to its activities in the SP-100 Program.

A Plan for Maintenance of Expendable Launch Vehicle Capability in Support of the New Space Transportation System

NASA
National Aeronautics and
Space Administration
Washington, D C
20546

Reply to Attn of C:LVN:mdd

OCT 13 1983

Honorable Don Fuqua
Chairman
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In compliance with the Presidential directive (NSD-94, May 16, 1983), as outlined in the enclosed press release, NASA intends to promote the effective application of private capital to the utilization of space by facilitating the transfer of the expendable launch vehicles (ELV's) to the private sector.

The Space Shuttle is now operational and current assessments of the manifest indicate that there is sufficient assurance of accomplishing the launch commitments to the ELV-class missions. In addition, the Shuttle manifest does include periodic vacant launch opportunities that are available to accommodate any callup, backup, or replacement type missions that may occasionally be required.

The enclosed plan for maintaining a U.S. expendable launch vehicle (ELV) capability to support the space transportation system is forwarded in response to the House Authorization Report 98-65. It should be noted that the requirement for an ELV plan pre-dates the President's policy of May 16, 1983, which directs NASA and DOD to transfer operation of ELV's to the U.S. private sector. This policy was the product of a detailed study by the Space Launch Policy Group, co-chaired by NASA and DOD, and the Senior Interagency Group (Space) recommendations accepted by the Administration to commercialize the U.S. Government's ELV programs.

Implementation of the President's policy has been initiated by NASA to transfer full program responsibility for Delta and Atlas Centaur launch systems to private industry. Therefore, the NASA plan is to retain these ELV capabilities in the U.S. Government no later than mid-1986 for Delta and mid-1987 for Atlas Centaur, at which time the capability will reside in private industry.

If there is any additional information which may be needed, please do not hesitate to call either me or someone on my staff.

Sincerely,

John F. Murphy
Assistant Administrator
for Legislative Affairs

Enclosures

cc:
Honorable Harold Volkmer
Honorable Larry Winn
Honorable Manuel Lujan

"A plan for maintenance of expendable launch vehicle capability in support of the new space transportation system"

The Space Shuttle is now operational and our current assessment of its manifest is that there is full assurance of accomplishing its launch commitments to ELV-class missions. Further, the Shuttle manifest now includes periodic vacant launch opportunities that are available to accommodate any callup/backup/replacement type missions that may occasionally be required.

Considering the above, in January 1983, NASA reassessed all Delta-class missions double-booked on Delta and Shuttle and determined that Delta launch requirements could be limited to 179 missions, nine in FY83, three in FY84, and three in FY85-86. These missions are those that could not acquire launch opportunities early enough on the Shuttle manifest or involve the last of a series of spacecraft that were designed for ELV launches and are physically incompatible with Shuttle.

The Delta Project at GSFC has current contracts for vehicle production with its industrial team--principally McDonnell-Douglas, Rocketdyne, and Thiokol, for fourteen vehicles through mission #184. Accordingly, we directed these contractors to complete production of vehicles for the expected 179 missions plus two (180, 181) as spares and terminate production of the last three vehicles which were now not needed (182-184). In addition, the rate of production was stretched out as much as possible to delay costs and the last vehicle (181) will now be delivered in fourth quarter calendar year 1984. The two spare vehicles (180, 181) could be utilized to launch two missions that for some unexpected reason cannot be accommodated on the Shuttle manifest if they, in fact, are not actually utilized by the ELV program as spares, or for other customer requirements.

During 1982, NASA contracted for critical long lead material items for eight additional Delta vehicles to maintain continuity of that capability because NASA had approximately two dozen additional missions double booked on both Delta and Shuttle and the total capacity of the Shuttle manifest to accommodate all those missions was not clear. Now that it is clear this material is not needed for the NASA program, it could be utilized for efficient start up of new production for a commercial operator right now in late CY83 for delivery as early as 1985.

The Atlas-Centaur did not require similar reassessment since vehicles are being built only to customized order for firm missions that cannot be accommodated by Shuttle. NASA had initiated phase-out of Atlas-Centaur production in 1979 when the advent of Shuttle was imminent and new Atlas-Centaur requirements did not appear for launches beyond 1981. Subsequent new orders (#59-65) from Intelsat led to a restart of production in 1980 for deliveries in 1982-84. Then, in 1981, the USAF added orders for five Atlas-H boosters and FLTSATCOM added orders for three missions (#66-68) with deliveries out to 1986. More recently, Centaur-in-Shuttle was approved for development, with production to start soon. The Atlas-Centaur contractor plants are operating at full capacity to accommodate this added workload and it is unlikely that new production for a commercial operator could start for a year or so. Atlas-Centaur vehicles are custom built to order and there will be no spares or long lead material available for a commercial operator to purchase.

NASA manages the Scout program now for the DOD. Scout vehicle production has been completed for a series of DOD callup missions at an expected launch rate of four per year in 1983-84 and two per year in 1985-87. There is no long lead material, nor spares production activity, in this program since adequate spares are in inventory. There has been no expression of interest in the Scout vehicle by the private commercial sector.

Considering the status of production of vehicle hardware for both Delta and Atlas Centaur noted above, it was recognized that the process of transferring these programs to the private sector to operate as a commercial venture should be initiated now. Accordingly, NASA formally solicited an expression of interest in such a venture by the private sector in Commerce Business Daily on 21 June 1983. Based on the response to that announcement, a "Solicitation Package" was released on 9 September 1983 for formal proposals from commercial offerors to lease government owned facilities, equipment and tools required to conduct the Delta and/or Atlas-Centaur programs subsequent to completion of the remaining firm NASA programs.

Delta has two launch gantries at Cape Canaveral, Florida, and one at Vandenberg AFB, California. Atlas-Centaur has two gantries at Cape Canaveral, although one will be dedicated to Centaur-in-Shuttle activities starting in 1985. Scout has gantries at Wallops Island, Virginia, and at Vandenberg. These will be available for commercial sector launches, or additional STS backup missions, using spare vehicles or new production vehicles, as required by NASA or the commercial sector, provided any requirement is identified early enough (two to three years) to allow time for support preparation.

NASA project teams for Delta and Atlas-Centaur involved civil service teams of roughly 50-70 people each to manage and provide technical oversight of the industrial teams that actually built and launched vehicles under contract to NASA. These civil service teams will be transferred to other NASA projects at their centers as the NASA firm ELV programs phase out. The contractor teams presumably will be retained under contract to the commercial operator. The Solicitation Package indicates that NASA will continue to contract for launch services through 1986 on Delta and 1987 on Atlas-Centaur to launch the firm NASA missions and any commercial missions could be added by contract on a noninterference basis. Further, it is specified that the operator can bid to take full responsibility for all launch activity if acceptable to NASA and its customers starting in 1985.

THE WHITE HOUSE

Office of the Press Secretary

For Immediate Release May 16, 1983

The President today announced that the U.S. Government fully endorses and will facilitate commercial operations of Expendable Launch Vehicles (ELVs) by the U.S. private sector. This policy applies to both those ELVs previously developed for U.S. Government use, as well as new space launch systems developed specifically for commercial applications. This policy is consistent with the President's National Space Policy and represents a positive step toward encouraging U.S. private sector investment and involvement in civil space activities.

The basic goals of U.S. space launch policy as stated in the President's Directive on Commercialization of Expendable Launch Vehicles are to: (a) ensure a flexible and robust U.S. launch posture to maintain space transportation leadership; (b) optimize the management and operation of the Space Transportation System (STS) program to achieve routine, cost-effective access to space; (c) exploit the unique attributes of the STS to enhance the capabilities of the U.S. space program; and (d) encourage the U.S. private sector development of commercial launch operations. The policy specifies that:

- The U.S. Government fully endorses and will facilitate the commercialization of U.S. Expendable Launch Vehicles (ELVs).

- The U.S. Government will license, supervise, and/or regulate U.S. commercial ELV operations only to the extent required to meet its national and international obligations and to ensure public safety. Commercial ELV operators must comply with applicable international, national and local laws and regulations including security, safety, and environmental requirements.

- The U.S. Government encourages the use of its national ranges for U.S. commercial ELV operations. Commercial launch operations conducted from a U.S. Government national range will, at a minimum, be subject to existing U.S. Government range regulations and requirements. Consistent with its needs and requirements, the U.S. Government will identify and make available, on a reimbursable basis, facilities, equipment, tooling and services that are required to support the production and operation of U.S. commercial ELVs.

- The U.S. Government will have priority use of U.S. Government facilities and support services to meet national security and critical mission requirements. The U.S. Government will make all reasonable efforts to minimize impacts on commercial operations.

- The U.S. Government will not subsidize the commercialization of ELVs but will price the use of its facilities, equipment, and services consistent with the goal of encouraging viable commercial ELV launch activities.

- The U.S. Government will encourage free market competition among the various systems and concepts within the U.S. private sector. The U.S. Government will provide equitable treatment for all commercial launch operators for the sale or lease of government equipment and facilities consistent with its economic, foreign policy, and national security interests.

- The U.S. Government will review and approve any proposed commercial launch facility and range as well as subsequent operations conducted therefrom. Near-term demonstration or test flights of commercial launch vehicles conducted from other than a U.S. Government national range will be reviewed and approved on a case-by-case basis using existing licensing authority and procedures.

Notwithstanding the U.S. Government policy to encourage and facilitate private sector ELV entry into the space launch market, the U.S. Government will continue to make the Space Shuttle available for all authorized users -- domestic and foreign, commercial and governmental -- subject to U.S. Government needs and priorities. Through FY 1988, the price for STS flights will be maintained in accordance with the currently established NASA pricing policies in order to provide market stability and assure fair competition. Beyond this period, it is the U.S. Government's intent to establish a full cost recovery policy for commercial and foreign STS flight operations.

IMPLEMENTATION

An interim working group under the Senior Interagency Group (SIG) for Space on Commercial Launch Operations will be formed and co-chaired by the Department of State and NASA. The Working Group will be composed of members representating the SIG (Space) agencies and observers as well as other affected agencies. Additional membership, at a minimum, will include the Federal Aviation Administration and the Federal Communications Commission. This group will be used to (a) streamline the procedures used in the interim to implement existing licensing authority, (b) develop and coordinate the requirements and process for the licensing, supervision, and/or regulations applicable to routine commercial launch operations from commercial ranges, and (c) recommend the appropriate lead agency within the U.S. Government to be responsible for commercial launch activities. Until a final selection of the lead agency is made, the Department of State will serve as the U.S. Government focal point for all inquiries and requests relative to seeking U.S. Government approval for commercial ELV activities.

BACKGROUND

The National Space Policy identified the STS as the primary launch system for the U.S. Government. The U.S. Government is in the process of phasing out its current ELV operations (i.e., Delta, Atlas, and Titan launch systems) as the capabilities of the STS become sufficient to meet its needs and obligations. Increasing private sector interest in continuing these ELV systems has resulted in requests for a U.S. Government policy on such activities. In addition, an increasing number of new enterprises have been established with the express purpose of developing commercial space launch capability.

The SIG (Space) was asked to review these issues and make recommendations to the President. This four-month interagency study concluded that a U.S. commercial ELV capability would offer substantial benefits to the Nation and would be consistent with the goals and objectives of the President's Space Policy.

The existance of a viable commercial ELV industry would add to the general economic vitality of the United States and provide the United States with a more robust space launch capability.

The creation of a domestic ELV industry would also maintain a high technology industrial base unequalled in the free world and provide jobs for thousands of workers while adding to the federal tax base of the U.S. and a number of states. Each commercial launch conducted in the U.S., rather than by foreign competitors, would strenghten our economy and improve our international balance of payments. Further, continuing commercial ELV operations are expected to spawn numerous spinoffs and supporting activities and strenghten the U.S. position in what is projected to be a growing commercial market, thereby providing substantial long-term economic benefits to the United States.

In addition to the general economic benefits, both NASA and the Department of Defense would benefit from continuing commercial ELV production and launch. It would provide a more robust U.S. Launch capability and offer a domestic backup for the Shuttle at essentially no cost to the U.S. Government. The private sector would assume all costs of ELV production now borne by the U.S. Government. There would also be a market for U.S. Government facilities and equipment that would otherwise be underutilized or no longer required. This would also reduce or eliminate U.S. Government close-out costs for discontinuing its ELV operations. It would provide a potential market for excess flight hardware, special purpose tooling and test equipment, as well as propellants which will become excess as the Air Force deactivates the Titan II ICBMs.

In summary, partnership between the U.S. private sector and the U.S. Government will strengthen the U.S. space launch capability, develop a major new industry, contribute favorably to the U.S. economy, and maintain U.S. leadership in space transportation.

# # #

NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

Reply to Attn of C:LVN:mdd

JUL 3 1984

Honorable Don Fuqua
Chairman
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As requested in the FY 1984 House Authorization Report 98-65, NASA has developed a Shuttle Marketing Plan for both short-term and long-term plans to establish an effective marketing activity. A copy of that plan is enclosed for your information.

If you should have any questions on the matter, please do not hesitate to call.

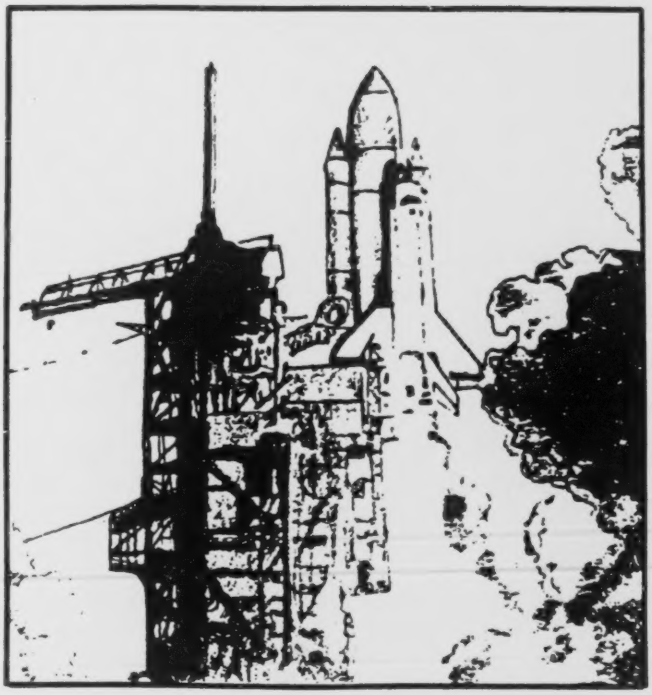
Sincerely,

John F. Murphy
Assistant Administrator
for Legislative Affairs

Enclosure

cc:
Honorable Harold L. Volkmer
Honorable Larry Winn, Jr.

THE SPACE TRANSPORTATION SYSTEM
MARKETING PLAN



NATIONAL AERONAUTICS
AND
SPACE ADMINISTRATION
WASHINGTON, D.C.

JUNE 1984

NASA STS MARKETING PLAN

NASA is committed to opening new avenues of opportunity for basic research and the commercial use of space by forging partnerships between Government, industry and academia. The same standard of excellence demonstrated by NASA throughout its history as a premier R&D organization will guide this new effort. NASA is in a unique position to lead this pioneering endeavor by helping demonstrate that work in space is useful and rewarding.

The Space Shuttle is one of the keys to the success of this endeavor having proved that it is the most useful and versatile space transportation system ever built. As a matter of National Policy, the STS program's highest priority is to achieve a fully operational, cost-effective Space Shuttle that will provide routine access to space. To accomplish this goal, NASA must: (1) meet the needs of our existing customer community and (2) stimulate additional demand by ensuring that the Shuttle, together with supporting services, provides new opportunities for the exploitation of the Space environment. We will achieve this by:

- providing our customers with a reliable launch service, including supporting technical assistance
- providing our customers with special opportunities, new services and schedule flexibility that meet their needs
- streamlining operations to minimize customer costs
- assisting in the development of new research, technology development, and commercial activities in space.

Both industry and Government are presently utilizing the Shuttle in a variety of beneficial ways. As a result of this need for access to space and the potential future demand, the launch service marketplace is becoming increasingly competitive.

The charter for making the STS available to meet these new challenges is from the President's National Space Policy of July 4, 1982, which states: "...STS capabilities and capacities shall be developed to meet appropriate national needs and shall be available to authorized users...domestic and foreign, commercial and governmental."

The NASA STS Marketing Plan defines the scope and direction that our marketing effort will take in the years ahead. Detailed strategies, implementing plans and activities will be developed and monitored to ensure the success of this effort to meet the needs of our customers.

We do not wish to be viewed as a supplier of a single service; rather, we strive to have our customers view NASA as a supplier of many important services capable of solving their problems, reducing their technical risks, and providing new opportunities for space-based ventures. Our customers will not find a more experienced technical cadre dedicated to providing these services anywhere in the world.

We commit to our motto..."WE DELIVER"... by using NASA's 25 years of experience and success to provide our customers with superior services.

APPROVED:
James M. Beggs
Administrator

JUN 29 1984

APPENDIX

FY-1984 STS DETAILED MARKETING PLAN

OFFICE OF SPACE FLIGHT

BACKGROUND

At 7:19 am EST, November 11, 1982, the world's newest space transportation service opened for business with the first operational flight of the Space Shuttle. STS-5 was launched from the Kennedy Space Center with a primary cargo of two commercial communications satellites, Satellite Business System's SBS-3 and Telesat Canada's Anik C-3. This marked the achievement of a major milestone for the National Aeronautics and Space Administration and for Shuttle marketing.

Since STS-5, the Shuttle Program has gained a number of communication satellite customers. STS-7 successfully deployed the Canadian Telesat-F and Indonesia's Palapa-B1 communication satellites. In addition, the Indian Insat-1B communication satellite was deployed on STS-8. On STS-11, Indonesia's Palapa-B2 and Western Union's Westar-VI were successfully deployed by the Shuttle, but failed to reach geosynchronous orbit because of upper stage motor problems on each spacecraft. Nonetheless, the Shuttle has demonstrated a suitability for delivering communications satellites to earth orbit as well as providing the foundation for many new activities in space. In addition, NASA has successfully entered into joint endeavor agreements with industry to place experiments in space, such as the McDonnell Douglas/Johnson & Johnson electropheresis MPS experiment on STS-6 which can form the basis for the creation of new industries and commercial efforts in space.

Marketing Demand

The demand for launch services and on-orbit services arises from three main customer segments:

1. NASA and Other Civil Government -- science applications, technology, meteorology and earth sensing programs.

2. Department of Defense -- programs for communications, meteorology, defense and surveillance.

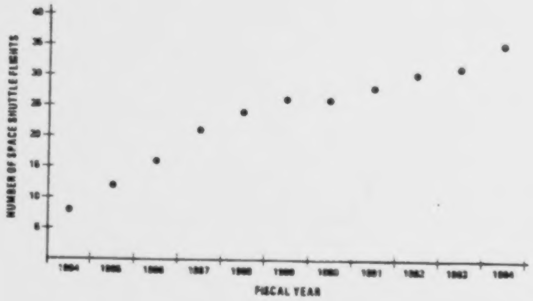
3. Commercial and Foreign Government -- programs for domestic communications, applications in materials processing and manufacturing, technology demonstration, science, world communications, foreign domestic communications, and earth sensing.

These segments create an estimated total free world demand for launch services, as shown in the figure on the next page, in terms of equivalent Shuttle flights. This demand forecast is consistent with other projections by the launch service competition and others in the space business.

All recent forecasts predict an increase in demand for access to space. To provide for that need, competitive launch systems have surfaced and are actively marketing their launch systems.

MARKET DEMAND PROJECTION

(EQUIVALENT SHUTTLE FLIGHTS WITH A 75% LOAD FACTOR)



Competition

With the potential increase in market demand the launching services market has experienced increased competition from foreign launch services. In the future, NASA expects the competition for customers to increase even more as the competing launching systems mature and new ones are available.

Currently, there are three major launch systems available to free world customers: U.S. ELV's, Arianespace, and STS. Others (Japan and China) are building capabilities to provide launch services, but to date they have indicated their intention to only provide domestic services. The U.S.S.R. has shown an interest to compete in the commercial market by submitting a bid to launch INMARSAT payloads. However, it is too early to predict their future intentions and the effect of their entry into the market. A close watch on the activities of these systems will take place to anticipate any movement to enter the competition. In the near term, the three major systems will be the main competitors for payloads that are not dedicated to domestic launch systems.

U.S. ELV Status

As currently manifested, U.S. Government-managed Expendable Launch Vehicles (ELV's) represent at least 3 percent of the commercial launching business between 1983 and 1998. According to the Battelle Outside Users Payload Model, U.S. ELV's carried approximately 60 percent of the commercial and foreign government payloads in 1982 and then will gradually reduce in future years. The current commercialization of U.S. ELV's will lead to more formal market share projections as that becomes a reality.

Arianespace Status

Arianespace is by far the largest competitor to the STS. Battelle estimates that should Arianespace win all the commercial and foreign government payloads, their market share will be roughly equivalent to the STS share through 1997.

Arianespace is a jointly owned company with partners coming from Germany, Belgium, Denmark, Spain, the United Kingdom, Ireland, Italy, The Netherlands, Sweden, Switzerland, and France. The French shareholders own the majority of the stock with 59.25 percent. Its activities include production of the Ariane operational launch vehicle, financing production, marketing and control of launching operations at the Guyana Space Center in South America.

The Ariane launch vehicle has been developed to support the European Space Agency (ESA) member nations space program. On average, this will amount to between two and two and one-half flights per year. This level of activity is not adequate to support a viable launch vehicle program. Thus, Arianespace is aggressively marketing the availability of the Ariane launch vehicle on a worldwide basis. They have designed their vehicle for the geosynchronous missions which include the communications satellites.

Their stated objective is to capture 25-30 percent of the world market between 1985 and 1991. Arianespace studies indicate that about 250 satellites will be put into orbit during this time frame. The Battelle High Model indicates about 260 of which about 170 will be going to geosynchronous orbit. Thus, Arianespace could expect to launch approximately 70-75 satellites during that seven year period. Depending on the number of dual payload flights, this would represent between 7 and 10 flights per year.

Arianespace currently has one launch complex at the Guyana Space Center and has the capability of supporting five to six launches per year. Ariane-4 will be launched from a new complex which has a separate integration area from the checkout and launch area. This will increase the Arianespace launch rate capability to about ten per year. The new launch complex is expected to be operational by the end of 1985.

Arianespace has developed seemingly effective sales literature that is quick to point out any Shuttle problems. They also have an attractive launch deferment plan and a very aggressive marketing department.

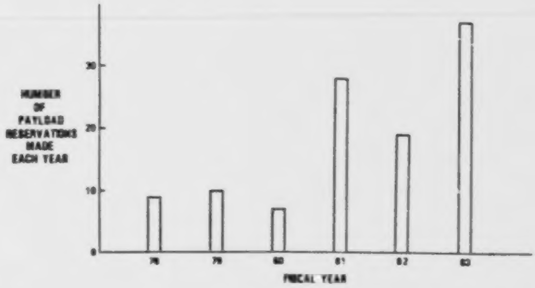
Currently, Arianespace has firm contracts for all launches through May 1986. In addition, they have at least 18 reservations and four additional contracts for launches for 1986 and beyond.

In summary, Arianespace appears to be the major competitor for the STS through 1997. Once Arianespace corrects development problems, they will aggressively pursue their stated objective to gain 25 to 30 percent of the free world launch services business for the time interval 1985 - 1991. The key to their success will depend primarily on their ability to consistently insert satellites into the proper orbit and to do it on schedule.

STS Status

Even with the competition from foreign launch services, the number of launch reservations on the Shuttle has had a remarkable increase in the last 12 months. The following graph shows the history of foreign and commercial payload reservations on the Shuttle. Over 110 of the current 130 reservations represent communications satellites scheduled to be launched over the next several years.

FOREIGN AND COMMERCIAL PAYLOAD RESERVATIONS



While our successes in communications satellites represent near term marketing successes, our long term business development has had equal success. The joint NASA/European Space Agency Spacelab mission, flown on STS-9, was a resounding success. Numerous experiments were successfully conducted that could lead to further development of scientific and commercial activities in space. In addition, the Small Self-Contained Payload (SSCP) or Getaway Special utilizes a NASA provided standard container to fly small payloads at unusually low cost. It is expected that some of the research conducted on the Getaway Specials will support the development of new, full size payloads. The Shuttle has flown 21 Getaway Specials and there are over 400 reservations for future flights. NASA has also entered into a number of Joint Endeavor Agreements with industry and some entire Shuttle flights have been reserved by payload brokers.

The current projected capacity of the Space Shuttle is at least 24 flights per year in 1988 and beyond. This capacity includes expanded launch capabilities through the use of the Vandenberg launch site for additional capacity and orbital inclinations. The need for additional capacity will be studied closely as new demand for launch services develop.

Shuttle marketing activities have met with much success, but they are still in a developmental stage. The Shuttle's primary competitor (Arianespace) has a fully developed and highly competitive marketing team. The NASA marketing team needs to be stronger and more sophisticated in order to successfully compete with other marketing efforts in the future since the competition will be providing increasingly reliable services, narrowing the gap with the Shuttle.

STRATEGIES

To successfully provide a superior space transportation service to our customers, NASA will implement the following basic strategies: 1) promote the use of space, 2) improve needed customer services, 3) create an environment for the customer that increases customer satisfaction with NASA, 4) develop STS capabilities into usable services.

Each of the strategies is dealt with independently in order to provide the basis for the detailed plans needed to carry them through. A single NASA manager will have the responsibility and authority to implement this plan by employing these strategies to meet the STS marketing objectives. Further, these strategies and the supporting activities are subject to changes which reflect changing customer needs or the environment.

1. Promote the use of Space- NASA and the STS have already received worldwide attention, but not all potential customers have been exposed to the Shuttle's specific benefits and unique capabilities, nor are they fully aware of the opportunities in space the Space Shuttle creates for them. An aggressive promotional effort, tailored to the needs of the marketplace, will be implemented emphasizing NASA's extensive experience and how the Shuttle can be used to help accomplish our customers' scientific and business objectives. Sales efforts will be directed toward those who are identified as potential STS customers to obtain launch commitments. This effort will take place through presentations and regular contact with individual customers as well as targeted audiences. Other government agencies who have influence with customers will also be targets of this activity. Promotional programs will also be directed toward others who influence customer decisions such as spacecraft manufacturers, trade associations, payload operators, and customers of payload products. All the activities in this area will be coordinated with the results of the Commercialization Task Force since the Office of Space Flight will participate as a key partner in the agency-wide space commercialization program.

2. Improve Needed Customer Services - Maintaining a competitive edge in the marketplace requires that NASA offer additional services to customers in areas in which NASA has not historically been involved. A dedicated effort will be undertaken to develop new and improved customer services. Initially, new services will be identified and implemented to facilitate customers obtaining financing, insurance, venture capital and alternate upper stage arrangements. Also, policies and procedures will be modified consistent with customer objectives. Any changes and new services will be based on extensive market research and customer feedback.

3. Create an Environment for the Customer that increases Customer Satisfaction with NASA - For the STS to remain competitive, an improved customer environment is needed. NASA will solicit and be receptive to customers' concerns and aggressively implement needed improvements that reduce the customers' costs and increase customer satisfaction. The STS launch support contractor will share in that responsibility. Some areas requiring early attention are the need for a single STS spokesman from "cradle to grave" for each customer, improvements in operations supporting customers' activities at the Field Centers and an increase in flexibility to respond to customer requirements. Also, a Customer Services Center will be developed to improve customer interfaces. Maintaining a responsive customer-oriented organization will become one of NASA's keys to retaining existing customers, as well as obtaining new customers in the future.

4. Develop STS Capabilities into Usable Services - The Space Shuttle is a complex system with a wide range of available, planned, and yet-to-be-defined services. NASA will develop new and unique services that will augment the basic services offered providing customers with revolutionary tools to further satisfy their objectives. On-orbit servicing and repair and satellite retrieval are new services that are being developed initially. Also, services that capitalize on the presence of man during scientific and commercial operations will be further developed, as well as standardized capabilities for handling experiments to help reduce research experiment costs.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: C:JJM:mdd

JAN 12 1983

Honorable Harold L. Volkmer
Chairman
Subcommittee on Space Science
and Applications
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In the FY 1984 NASA Authorization Report 98-65, the Committee requested that NASA report on the status of long-term plans for technology development (including power sources) for deep space missions beyond Galileo and the International Solar Polar Mission. The report is enclosed.

The report covers technologies applicable to missions to explore both the inner and outer planets, as well as, comets and asteroids. The major elements of the NASA research and technology activities supporting these missions are presented. Within each element, promising near-term and far-term technological opportunities that could greatly enhance the conduct of the missions are identified.

In House Report 98-65, the Committee requested that the NASA Advisory Council review the adequacy of current NASA Space Research and Technology programs supporting future planetary missions. The Council's Ad Hoc Subcommittee will be chaired by Mr. Robert Walquist, Vice President and General Manager of the TRW Space and Technology Group. The Ad Hoc Subcommittee, composed of members from both the Solar System Exploration Committee and the Space Systems and Technology Advisory Committee, will begin the review in February 1984 and plans to complete it by April 1984. At that time we will report the findings and conclusions of the study to you.

I hope the approach we have undertaken will be satisfactory. Please call me if you have any questions.

Sincerely,

Jack Murphy

John F. Murphy
Assistant Administrator
for Legislative Affairs

Enclosure

RESEARCH AND TECHNOLOGY FOR SOLAR SYSTEM EXPLORATION MISSIONS

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

DECEMBER 1983

RESEARCH AND TECHNOLOGY FOR SOLAR SYSTEM EXPLORATION MISSIONS

NASA has recently reformulated the Nation's Solar System Exploration Program in response to the findings and recommendations of the Solar System Exploration Committee (SSEC) of the NASA Advisory Council. The SSEC is composed of outstanding solar system research scientists and engineers from universities, industry, and government. Their report (published May, 1983) recommends a core program based on fundamentally important scientific objectives but achievable within significantly reduced costs. For instance, this core program envisions progressive technology advancements but does not require quantum leaps in enabling technology. The core program emphasizes the inner bodies (especially Venus, Mars, and the Moon) and the more primitive bodies (comets and asteroids). The outer planet missions of the core program are the Titan Probe, Saturn Probe, Saturn Orbiter, and Uranus Probe. Finally in regard to program formulation, the SSEC recently recommended augmenting the core program as soon as feasible with two technologically challenging missions of larger scope, the Mars Sample Return Mission and the Comet Nucleus Sample Return Mission.

The recommended implementation approach for the inner planetary bodies is a series of Planetary Observer Missions. Such a series of missions would allow for the orderly infusion of advanced technology. These Planetary Observer Missions, the first of which is the Mars Geoscience/Climatology Orbiter, would be based on derivatives of existing production-line Earth orbital spacecraft to implement low cost missions with focused science objectives. These existing spacecraft designs will be augmented with scientific instrument packages appropriate to the mission. By taking advantage of high inheritance from existing, demonstrated spacecraft, Planetary Observer Missions will not demand major technological advances. However, advanced technology will bring spacecraft systems and science instrumentation to the stage where they can be achieved economically.

The outer planet and primitive body missions would be implemented using a single new modular spacecraft design, the Mariner Mark II. The design will provide for flexibility to accommodate mission-peculiar requirements and will allow for hardware and software reconfigurability to accommodate different mission requirements. Since they are more demanding technologically, these missions will benefit significantly from such technology enhancements as

- X-Band solid state communications components
- Multi-source power conditioning and high voltage power distribution

- Microstep actuators
- Improved star sensors
- Fiber optics rotating sensors
- Adaptable science platform pointing
- Modular RTG's

The recently recommended missions of larger scope will require considerable technological advancement. The Mars Sample Return Mission depends on technology advances in such areas as computer capability, automation, autonomous control, entry body aeromaneuvering, high performance, low-thrust propulsion, communications, mechanisms, and space power. Two of the more challenging elements of this mission are the automated, autonomous rover capable of up to 100 km range while being commanded only once per day, and the return to Earth of the samples from an uncontaminated Martian environment. The Comet Nucleus Sample Return Mission similarly depends on technological advances in autonomous, automated operations and would need the continued development of electric propulsion technology.

Advanced technology programs to address the near-term needs of the recommended core program, the somewhat more distant needs of the recommended augmentation missions, and even longer term requirements, are shared between the Office of Space Science and Applications (OSSA) and the Office of Aeronautics and Space Technology (OAST). In FY 1984, OSSA has allocated approximately $5 million for the development of advanced instrument systems, the development of a multi-mission planetary spacecraft operations facility, and - in a joint effort with OAST and with the Office of Space Tracking and Data Systems (OSTDS) - the development of a new X-band solid state communications system. In terms of near-term application, OAST has been developing the technology for an advanced digital processor to handle the larger volume of data that will be returned by the synthetic aperture radar of the Venus Radar Mapper mission, the first mission of the SSEC core program. Other focussed efforts within the ongoing OAST program include the development of an advanced solid state imaging sensor (CCD) and the continued development of electric propulsion systems.

The detailed planning of the technology programs to meet the long term needs of both the recommended core program and the recently recommended missions of larger scope will continue during the current fiscal year. While some of the technology needs for these missions are evident, further work needs to be undertaken to define the technology requirements in detail and to establish priorities.

The overall OAST Space Technology Program develops generic technologies to support the Nation's space activities. The following paragraphs will describe elements of the program which are of particular interest to Solar System Exploration -- including the deep space missions. Support for these elements is on the order of $30 million in FY 1984. As these technologies are generic, they are applicable not only to Solar System Exploration, but also to Astrophysics, Satellite Communications, earth remote sensing and other programs. The table and text are organized as the research is performed -- in discipline or subsystem elements.

AEROTHERMODYNAMICS - Aeromaneuvering is an option for the Mars Sample Return Missions. In general, an aeromaneuvering planetary mission, which can encounter rarefied to continuum flow regimes, requires the accurate definition of aerodynamic and aerothermodynamic environments. This capability is required to define the probe configuration and controls and to minimize the weight of the thermal protection system. Rarefied flowfield codes, using a recently developed probabilistic simulation for gas behavior, are now being developed to predict low-orbit flowfields and jet plume-vehicle interaction and contamination effects. Current research will be used as benchmarks for further research on methods for calculating vehicle aerodynamic and aerothermodynamic characteristics. High-temperature gas chemistry effects, which can significantly alter the aerothermodynamic environment and impact the overall design of the spacecraft, are extensions to be added to the benchmark codes.

Aerothermal analysis methods are needed for entry probes/decelerators with extensions to include high lift-to-drag aeromaneuvering entry configurations. These analyses are applicable to planetary aerocapture vehicles, such as envisioned for a Mars Sample Return Mission. The aerodynamic and aerothermodynamic analysis modules for system synthesis are intended to provide the capability for conducting systems analyses and determining technology sensitivities for various spacecraft and probe configurations in a variety of missions. Consideration is being given to the use of flight tests in the late 1980's to provide a data base in aerodynamics, aerothermodynamics, materials, and controls technologies needed for advanced aeromaneuvering vehicles, such as those planned for the planetary program.

MATERIALS AND STRUCTURES - Research thrusts applicable to planetary missions include the definition and characterization of environmental effects on materials, the development of aeromaneuvering entry long-life structural materials, and structural techniques to accommodate flexible spacecraft or appendages. One major concern is defining the mechanisms and control of contamination of planetary spacecraft from outgassing products. Current modeling technology for contamination and its effects, and of spacecraft/environment interactions, will be improved starting with available experimental data to aid in understanding transport and condensation of spacecraft contaminants. Eventually, it will be possible to predict the interaction of complex environmental factors and their effects on spacecraft hardware.

For long life application in high radiation planetary environments, current research on radiation resistant polymers and dimensionally-stable composite structures will be extended for scientific instruments, antennas, and structures. Current research on flexible ceramic, advanced thermal protection systems have the potential for significant advances applicable to thermal protection for aeromaneuvering missions.

Extensions of materials and mechanisms research for moving elements of a spacecraft will lead to advanced traction drives that will greatly reduce vibrations and backlash difficulties in designing structures for science platforms.

SPACE ENERGY SYSTEMS - Planetary exploratory missions of the future will require long-life energy sources, delivered economically with a modest weight. Current research includes photovoltaics, advanced power systems, and technologies for the management and distribution of electrical and thermal energy. The emphasis in photovoltaics is to develop lightweight solar arrays possessing very high specific power. Advances in the ultrathin silicon solar cell, transparent gallium arsenide cells, cascaded cells, low mass blanket technology and deployment structures, radiation resistance, and cell efficiencies will be incorporated in new array concepts and designs. A five-fold improvement over the 66 W/kg state-of-the-art Solar Electric Power array should be realized.

In battery technology, research is aimed at a very high energy density (>300 Whr/kg), long storage life, high rate primary lithium batteries to provide the capability needed for planetary probes. Efforts to develop high energy density, long cycle life secondary lithium and nickel hydrogen batteries could provide the capability needed for orbiting and lander/rover missions.

Advanced power management and distribution research is aimed at high voltage DC conversion and distribution systems, high voltage and high frequency AC conversion and distribution systems, solid state switching, and autonomous operational systems to reduce overall energy system initial and operating cost, complexity and mass. Advanced concepts for heat rejection, such as the liquid droplet radiator, are being evaluated and approaches for significant improvement in the transport and acquisition of heat are also under study.

In the long term, power over a wide range from kilowatts to megawatts for time periods up to ten years can be envisioned. OAST is part of a tri-agency program (SP-100) to advance nuclear power system technologies to meet high power, long life requirements. NASA is primarily involved in power conversion -- advanced thermoelectric materials and advanced dynamic engines --as well as system integration.

COMMUNICATIONS - The primary emphases in communications technology for planetary missions are reliability and energy efficiency. Traveling Wave Tube (TWT) amplifiers, currently used in planetary communications systems, are known to have a finite operating lifetime due to cathode depletion. In contrast, solid state power amplifiers hold the promise of almost unlimited operating life; consequently, research on solid state X-band power amplifiers is included as an option for potential use on future planetary missions. However, with the rapidly rising cost of electric power for planetary missions, energy efficiency is growing in importance. Recent advances in TWT technology, such as the dynamic velocity taper and the diamond heat sink, have more than doubled the efficiency of the TWT. Except for very low power operation, the TWT is more energy efficient than the solid state power amplifier, and, as a result, may continue to be used for planetary missions.

Ongoing research on monolithic microwave integrated circuits (MMIC) indicates that such devices could be a potential alternative to the solid state power amplifier and the TWT. Applied as transmitters, for example, an array of monolithic microwave integrated circuits might be used to produce an electronically steered microwave beam as an antenna conformable to the spacecraft body, or as a feed for a reflector. Electronically steered antenna technology might be especially effective in the multipath environment faced by a Mars rover vehicle.

Optical communications may prove to be the most efficient system in terms of weight and spacecraft power consumption. Although key components of a planetary optical communications system have yet to be developed, research is underway to increase the output power of laser diodes and to study electronic steering of laser beams.

CONTROLS - Mission complexity and duration and distance to the spacecraft increase the need for control systems that reduce operations costs by functioning autonomously for years. The Mars Sample Return and the Comet Nucleus Sample Return Mission each place extreme demands on several control technologies, including systems identification, fault tolerant techniques, advanced adaptive control, and new hierarchical control concepts.

Systems identification technology enables the on-board control system to identify the in-flight dynamic behavior of spacecraft, in order to ensure sufficient long-term control performance. To improve control system reliability, research is underway in advanced sensors and actuators, and fault tolerance management techniques. Several long life control system sensor and actuator concepts are in various phases of research, with emphasis on local integrated microprocessors and integrated optics. Research on fault tolerant management techniques is focused on identifying the design methods that incorporate reliability considerations into the spacecraft control system and on defining control system operating techniques to maintain maximum control performance in the presence of system or spacecraft faults.

Extensions of adaptive control technology currently under development will provide control systems with the capability to measure and modify performance. This low level of control decision management is based on the ability to gather large amounts of data from fault detection and systems identification technology. Adaptive control systems can compensate for unknown or uncertain system dynamics and environmental disturbances which degrade control performance. Hierarchical control is an even more advanced level of adaptive control, with the ability to make high level decisions within the control system. Control algorithms that can identify optional decision paths for achieving multiple objectives simultaneously would enable autonomous control system operation for missions where human intervention may not be possible.

ELECTRONICS/SENSORS - One of the main mission requirements is the remote sensing of planets and primitive bodies and their environments. This can be accomplished in two ways: either actively or passively. Passive sensing relies on detecting the radiation being emitted from the planet and its environment due to their being at a finite temperature. Current research in this area is focussed on large imaging arrays. Research is being conducted to increase the size of the arrays currently being incorporated into the Space Telescope and Galileo systems by increasing the number of detector pixels and at the same time extending their frequency response from the near infrared to the low energy x-ray portion of the electromagnetic spectrum.

For the far infrared and submillimeter portions of the electromagnetic spectrum, research is being conducted on both direct and heterodyne detectors. In the latter case, current research includes submillimeter wave components for heterodyne detection systems with potential application to an instrument package for a deployable reflector. Research is also being conducted to adapt microwave radiometer systems, successfully employed in earth observations of geophysical parameters, to future planetary missions. Work is concentrated on miniaturization, improved sensitivity, and wavelength response opimization. In the former area, new materials are being developed with the required frequency response in the far infra-red and submillimeter portions of the spectrum and with enhanced quantum efficiency.

Direct detectors must be cooled in order to reduce noise. Current research is directed toward efficient, space-qualified, long life reliable coolers employing active sterling and Joule-Thompson cycle refrigerators and passive radiating techniques for high and low heat loads.

Active sensing requires an onboard source to illuminate the planetary surface or environment. An example of this is the synthetic aperature radars (SAR) successfully employed in earth remote sensing. Current research is devoted to multiple frequency SARs employing phased array beam steerable antennas. These systems employ microwaves for the radiating source. Laser sources are also possible. Currently, research is being conducted on laser radars (LIDAR) and differential absorption LIDAR for the remote sensing of planetary atmospheric parameters such as chemical species, wind velocity, pressure, temperature, and geophysical parameters.

Because of the expected limited bandwidth, future spacecraft will require a high degree of autonomy. Current research is focussed on the implementation of artificial intelligence systems for decision making. In support of this software, advanced electronic systems are needed. Since some missions will need to operate reliably for up to 15 years in a hostile radiation environment, the electronics must be relatively tolerant to single event upset and radiation degradation. Current research in cooperation with the DOD in solid state physics is dedicated to the understanding of the physical mechanisms of radiation damage and methods of rectification. NASA is currently supporting DOD in the preparations for a space flight to investigate the response of large scale integrated electronic circuits to the hostile radiation environment. In conjunction with research on hardware, work is ongoing on methods for fault tolerant computing and various redundant networking systems to rectify the single event upset problem.

Innovative methods for growing crystals, atomic layer by atomic layer, are being exploited to create new devices whose electronic and optical properties are tuneable over an exceedingly wide range of values. This unusual phenomena could find immediate application to wide band tuneable detector arrays, filters, mixers, and smart sensors.

PROPULSION - Research to support a high performance space-based Aeromaneuvering Orbital Transer Vehicle (OTV) is part of the current base technology program. A space-based OTV could benefit the planetary exploration program, when used in an expendable mode, by providing improved payload performance. The technologies being pursued to enable this vehicle are high-performance LOX/hydrogen propulsion, aeromaneuvering techniques, and cryogenic fluid management in zero gravity.

Research on integrated oxygen/hydrogen primary and auxiliary propulsion systems could provide spacecraft system options for improved performance. Attitude control class system options should result from the current research on oxygen/hydrogen system for drag makeup and attitude control functions. In addition, a simple, low thrust oxygen/hydrogen propulsion system might significantly benefit a Mars Sample Return mission by providing a high-performance system (compared to storables) for at-destination orbit changes. This option would utilize high reliability pump and combustor technologies to satisfy mission life and risk requirements. Long-term, low loss storage of cryogenic propellant could also have a significant impact on the payload data returnof a Mars Sample Return Mission.

Electric propulsion will be of particular benefit to planetary missions, such as the Comet Sample Return Mission. Current research is providing a technology base for the initial use of electric propulsion. In the post 2000's, a very high-performance (Isp>1500 sec), high-thrust (>100 lbs) propulsion system may be available. There is a need to reduce the transportation costs of moving massive quantities of terrestrially-produced propellants for in-space operations. Such technology could be applied to planetary orbit insertion propulsion systems. Ion thruster system technology is being advanced for solar and nuclear powered planetary propulsion.

More advanced propulsion concepts, such as the use of beamed energy and electrically enhanced launchers, are in the early phases of conceptual definitions. Another propulsion alternative may emerge from the technology to make use of non-terrestrial propellant sources.

SUMMARY

Both OAST and OSSA are supporting the technology needs of the reformulated Solar System Exploration Program. The detailed planning of the technology programs to support solar system exploration will continue during the current fiscal year. Both OSSA and OAST are supporting the near term needs of the core program and OSSA is continuing to define the needs of the larger scope missions. OAST is supporting the broad generic technologies, many of which will benefit the Solar System Exploration Program.

TECHNOLOGY FOR SOLAR SYSTEM EXPLORATION MISSIONS

PROGRAM ELEMENT	1980	1990	2000	2010	SPECIFIC GOAL
AEROTHERMODYNAMICS	FREE-MOLECULE JET PLUME INTERACTIONS CONTAMINATION PREDICTION ANALYSIS METHODS FOR AEROMANEUVERING ENTRY				0 RAREFIED GAS DYNAMIC CODES 0 HIGH-TEMP GAS REACTION DATA
		ADVANCE HEATING-METHODS FOR VEHICLE SYNTHESIS			0 HEAT TRANSFER PREDICTION
	AEROASSIST FLIGHT EXPERIMENT ENTRY FLIGHT EXPERIMENT				0 ENTRY DATA BASE
MATERIALS AND STRUCTURES	MONO/DIATOMIC CHEMICAL INTERACTIONS AT HIGH HEAT FLUX	CONTAMINATION TRANSPORT & CONDENSATION	COMPLEX ENVIRONMENTAL INTERACTIONS		0 CHARACTERIZE ENVIRONMENT EFFECTS
		FLEXIBLE CERAMICS FOR AEROBREAKING			0 AEROBRAKE & ENTRY MATERIALS
		RADIATION RESISTANT POLYMERS	DIMENSIONALLY STABLE COMPOSITE STRUCTURE		0 LONG LIFE SYSTEMS
		ADV. SYSTEMS FOR TRACTION DRIVERS			0 LONG LIFE MECHANISMS
SPACE ENERGY SYSTEMS		1 AU LIGHTWEIGHT ARRAY		10 AU LIGHTWEIGHT ARRAY	0 LIGHTWEIGHT SOLAR ARRAYS
		ADVANCED POWER CONVERSION	HIGH VOLTAGE/POWER DISTRIBUTION BREADBOARD		0 ADVANCED POWER ARRAYS
	NUCLEAR REACTOR POWER SYSTEMS TECHNOMOGY		NUCLEAR POWER		0 NUCLEAR POWER
	LITHIUM PRIMARY BATTERIES BIPOLAR N,H$_2$ BATTERIES		ADVANCED STORAGE (KWHR/kg)		0 LONG-LIFE HIGH ENERGY DENSITY, BATTERIES
		LIQUID DROPLET RADIATOR	MULTI MEGA WATT THERMAL MGT		0 HIGH PERFORMANCE HEAT REJECTION SYSTEMS

TECHNOLOGY FOR SOLAR SYSTEM EXPLORATION MISSIONS

PROGRAM ELEMENT	1980	1990	2000	2010	SPECIFIC GOAL
COMMUNICATIONS	HIGH-EFFICIENCY TWTA	INTERGRATED OPTICS MODERATE DATA LASER LINKS			O DEEP SPACE COMMUNICATIONS DATA LINKS
	X-BAND SOLID STATE COMPONENTS	X- & Ka- BAND MMIC FEED ARRAYS & ANNTENNAS	ELECT. BEAM STEERED ARRAY FED ERECTABLE HIGH GAIN ANTENNAS		
CONTROLS	CENTRALIZED CONTROL	DISTRIBUTED CONTROL	ADAPTIVE HIERARCHICAL CONTROL		O CONTROLS FOR FLEXIBLE SPACECRAFT
		FLEXIBLE/MODULAR ADAPTIVE CONTROL			
	GROUND CONTROL STATION DESIGNS	TELEOPERATOR CONTROL STATION	MULTI-ARM, MULTI-FUNCTIONAL TELEOPERATORS		O AUTOMATED FUNCTION GUIDELINES
ELECTRONICS/SENSORS	RADIATION HARD. DEVICES	LARGE-SCALE TUNABLE IR SUPERLATTICE ARRAYS			O RELIABLE SPACE
		ADAPTIVE INTELLIGENT OPTICS			
		SPACE QUALIFIED LASERS			
	800X800 CCD	1024X1024 CCD ON-CHIP COLOR	ADVANCED IR		O ADVANCED DETECTORS AND SENSORS
		ACTIVE CRYOGENIC COOLERS			O LOW/ULTRA-LOW TEMP. REFRIGERATOR SENSOR COOLING

TECHNOLOGY FOR SOLAR SYSTEM EXPLORATION MISSIONS

PROGRAM ELEMENT	1980	1990	2000	2010	SPECIFIC GOAL
PROPULSION	VARIABLE THRUST HIGH Pc LOX/LH2 ENGINE TESTING	HIGH-PERFORMANCE VARIABLE THRUST LOX/LH2 ENGINE			O HIGH-PERFORMANCE PROPULSION SYSTEMS
		INTEGRATED PRIMARY AND AUXILIARY PROPULSION SYSTEMS	NUCLEAR ELECTRIC PROPULSION HIGH THRUST/Isp CONCEPT FEASIBILITY		
		ADVANCED LOW THRUST ELECTRIC PROPULSION	BEAMED POWER	EARTH/LUNAR LAUNCHERS	O ADVANCED PROPULSION
			NON-TERRESTRIAL PROPELLANT SOURCES		O AUTOMATED PROPELLANT PRODUCTION
	CRYO-FLUID TRANSFER FLIGHT EXPERIMENT	LOW-LOSS CRYO TANKAGE ACTIVE REFRIGERATION			O LOW-LOSS STORAGE AND TRANSFER OF CRYO FLUIDS IN ZERO-G

REPORT OF THE AD HOC SUBCOMMITTEE ON SPACE RESEARCH AND TECHNOLOGY FOR FUTURE PLANETARY MISSIONS

2 MAY 1984

PREPARED FOR

NASA ADVISORY COUNCIL

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I. EXECUTIVE SUMMARY

In response to a request from the U. S. Congress, House Committee on Science and Technology, an Ad Hoc Subcommittee on Space Research and Technology was formed to conduct an assessment of the adequacy of the current space research and technology programs to support future planetary missions. This report comprises the Subcommittee's response to this Congressional request.

The space research and technology program is a broadly based technology program which addresses the major technology elements involved with spacecraft design and development, including spacecraft electric power, propulsion, thermal control, structures, data handling, communications, and attitude control. The above are long-standing activities within NASA and are generic to any spacecraft program. In addition, there are specific technology activities (such as Aerothermodynamics) which are associated with spacecraft passing through planetary and/or comet atmospheres that are not generic in nature but are focused more on the needs of a specific class of missions.

In the space research and technology program, the effort spent on generic technologies is appropriately much greater than for mission-specific technologies. However, this Subcommittèe questions whether some of the mission-specific technologies are receiving adequate support. In addition, the relatively constant dollar budget over the past several years for total space research and technology has become a decreasing fraction of the total NASA budget. NASA should examine whether a decreasing budget fraction is appropriate for space research and technology when the Agency is embarking on a reinvigorated planetary program, which contains a number of mission-specific technology needs in addition to the generic technologies mentioned above. Also, NASA's new initiative on the Space Station will place additional technology development requirements (and hence budget requirements) upon NASA. Without additional technology development funds, Space-Station-unique technology development will occur at the expense of planetary program mission-specific technology development.

The currently planned space research and technology program supports most of the technology needs of the Core missions of the SSEC recommendations. However, it should be noted that technology adequacy for the Core missions should occur almost by definition -- because Core missions basically were selected to require only existing technology. However, some exceptions were found, primarily in the mission-specific technologies.

The Subcommittee has identified a number of technology areas that need to be strengthened to supply proper support for the SSEC-identified list of future planetary missions. The most serious deficiencies are associated with the programs in the Augmentation missions category. The absence of identified technology will prevent the Augmentation missions they enable from becoming approved and thus present a self-fulfilling prophesy: the technology is not needed because there will be no mission, and there will be no mission because the needed technology is not available. The most deficient area appeared to be technology for surface/core sampling of various bodies in the solar system.

Specific recommendations from the Subcommittee are as follows:

1. The mission-specific technology needs of the SSEC-recommended Core planetary missions and the overall technology needs of the Augmentation missions be identified and evaluated for their proper emphasis in the space research and technology program. Cooperation between OSSA and OAST should be fully developed as the means of assuring that technology needs and the breadth of their applicability are well understood.

2. Technologies needed to enable the planetary Augmentation missions must be developed or those missions will never be approved. Specific technology activities needed for future planetary missions include the following eight areas:

1) aeromaneuvering and aerocapture with controlled lift,
2) autonomous command/control,
3) surface/core sampling activities,
4) materials and structures,
5) robotics,
6) long-life, small power sources,
7) advanced/adaptive signal and data processing, and
8) electric propulsion.

II. INTRODUCTION

The Ad Hoc Subcommittee on Space Research and Technology for Future Planetary Missions was formed by NASA as a subcommittee to the NASA Advisory Council (NAC) in response to a request from the U. S. Congress, House Committee on Science and Technology*. The charter of the Subcommittee was to conduct an assessment of the adequacy of the current space R&T programs to support future planetary missions. The Subcommittee met on February 29 and March 1, 1984, at NASA Headquarters. This report of the subcommittee to the NAC comprises the response to the Congressional request.

The Subcommittee membership included representatives from both the Space Systems Technology Advisory Committee (SSTAC) and the Solar System Exploration Committee (SSEC) of the NAC:

SSTAC Members

Robert L. Walquist, TRW - Chairman
George Gamota, University of Michigan
Abraham Hertzberg, University of Washington
Robert Herzberg, Lockheed Missiles and Space Co.
James Lazar, Argonne National Laboratory
Gene Strull, Westinghouse Electric Corp.

SSEC Members

Edward Danielson, California Institute of Technology
John Niehoff, Science Applications, Inc.
Fred Scarf, TRW

Executive Secretary

Lana Couch, NASA

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*Report of the U. S. Congress, House of Representatives Committee on Science and Technology, "Authorizing Appropriations to the National Aeronautics and Space Administration for Fiscal Year 1984," No. 98-65, 15 April 1983.

Topics Reviewed on Future Planetary Needs and Requirements

- **Mariner Mark II**
- **Augmentation Missions**
    - **Mars Sample Return**
    - **Comet Nucleus Sample Return**
- **Probes and Penetrators**
- **Sensors and Instrumentation**

Topics Reviewed on Space Research and Technology Applicable to Future Planetary Missions

- Aerothermodynamics
- Materials and Structures
- Controls
- Electronics and Sensors
- Communications
- Power and Electric Propulsion
- Chemical Propulsion

III. REVIEW OF THE PROGRAMS

A. Planetary Exploration Program

In 1980 the NASA Advisory Council established the Solar System Exploration Committee (SSEC) and asked the committee to formulate a long range program of planetary missions that would be consistent with the Space Science Board recommendations and realistic NASA fiscal restrictions. This initiative was motivated by the fact that support for planetary research had declined very significantly during the post-Viking time period (Figure 1 shows the yearly variation in funding for NASA's total space science program, and for the individual elements; this graph clearly illustrates since around 1975 the continuous shrinkage of support for planetary programs during a period when life science research funding has continued at a steady level and physics/astronomy support has increased noticeably).

In 1982 the SSEC agreed on the strategy for a relatively constrained "Core Program" and this program is described in the report: "Planetary Exploration Through Year 2000." The recommended Core missions are listed in Table 1. In 1983 the SSEC began considering a group of "Augmentation" missions. This analysis is not yet complete, but in several areas, the SSEC choices for Augmentation missions have been clearly determined (Table 2). The SSEC selections are consistent with earlier Space Science Board recommendations.

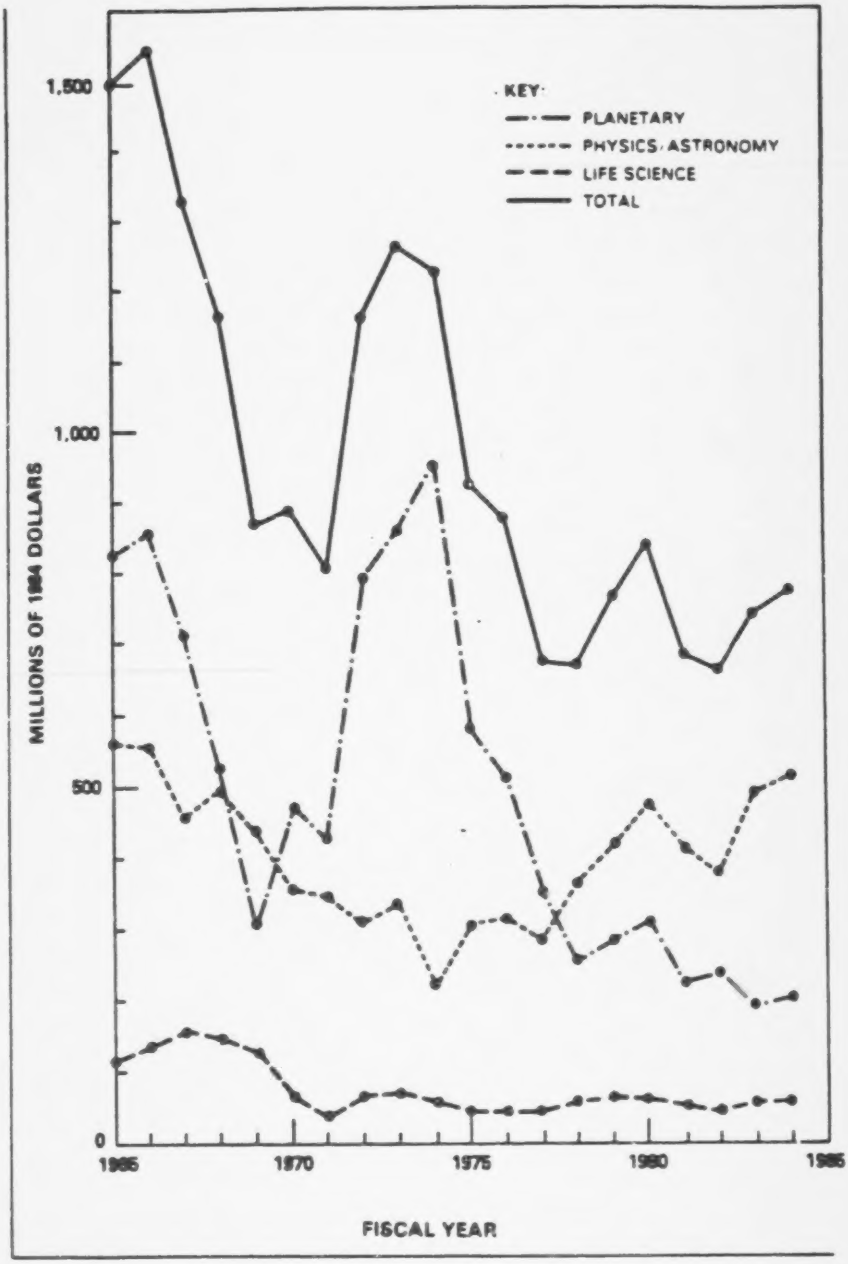


FIGURE 1. SPACE SCIENCES FUNDING

]

TABLE 1

Recommended Core Program

- Venus Radar Mapper
- Mars Geoscience/Climatology Orbiter
- Comet Rendezvous
- Titan Probe

- Mars Aeronomy Orbiter
- Mars Probe Network
- Venus Atmospheric Probe
- Lunar Orbiter

- Saturn Probe
- Saturn Orbiter
- Uranus Probe

- Comet Atomized Sample Return
- Multi Main-belt Asteroid Orbiter and Flyby
- Earth Approaching Asteroid Rendezvous

TABLE 2. SSEC RECOMMENDATIONS FOR AUGMENTED PLANETARY PROGRAM

RECOMMENDED MISSIONS

- MARS ROVER/SAMPLE RETURN
- COMET SAMPLE RETURN

The SSEC Core program has generally been designed to minimize any requirements for technology development needed to enable, rather than enhance, the missions. However, for a few of the Core missions, it became evident that there were significant technology development issues. Partly because of the technology developments needed for its surface penetrators (primarily RTG power and decelerator design), the SSEC has recommended that the Mars Probe/Network mission be placed toward the end of the Core list. However, one relatively near-term mission with very high priority, the Saturn Orbiter/Titan Probe (a combination of two of the original Core missions), requires OAST support to enable the mission. Here the requirements include electric power technologies to allow unusually long probe reisdence time in Titan's atmosphere.

A Mariner Mark II spacecraft is needed for those Core missions that go beyond the orbit of Mars to provide additional capability over the Earth orbiters planned for use on the planetary close-in missions. The Mark II spacecraft is now being developed to be a modular vehicle for the more demanding missions in the SSEC Core set.

The Augmentation missions listed in Table 2 have a very strong reliance on the development of new technologies for their implementation. These missions are obviously the most technically demanding of any being considered for the future planetary program. However, if the enabling technologies are not developed, these missions cannot win new start approval. The specific technology areas requiring additional attention are described in detail in Section IV.B., but in general fall in the categories of automated, remote operation and sample acquisition and return.

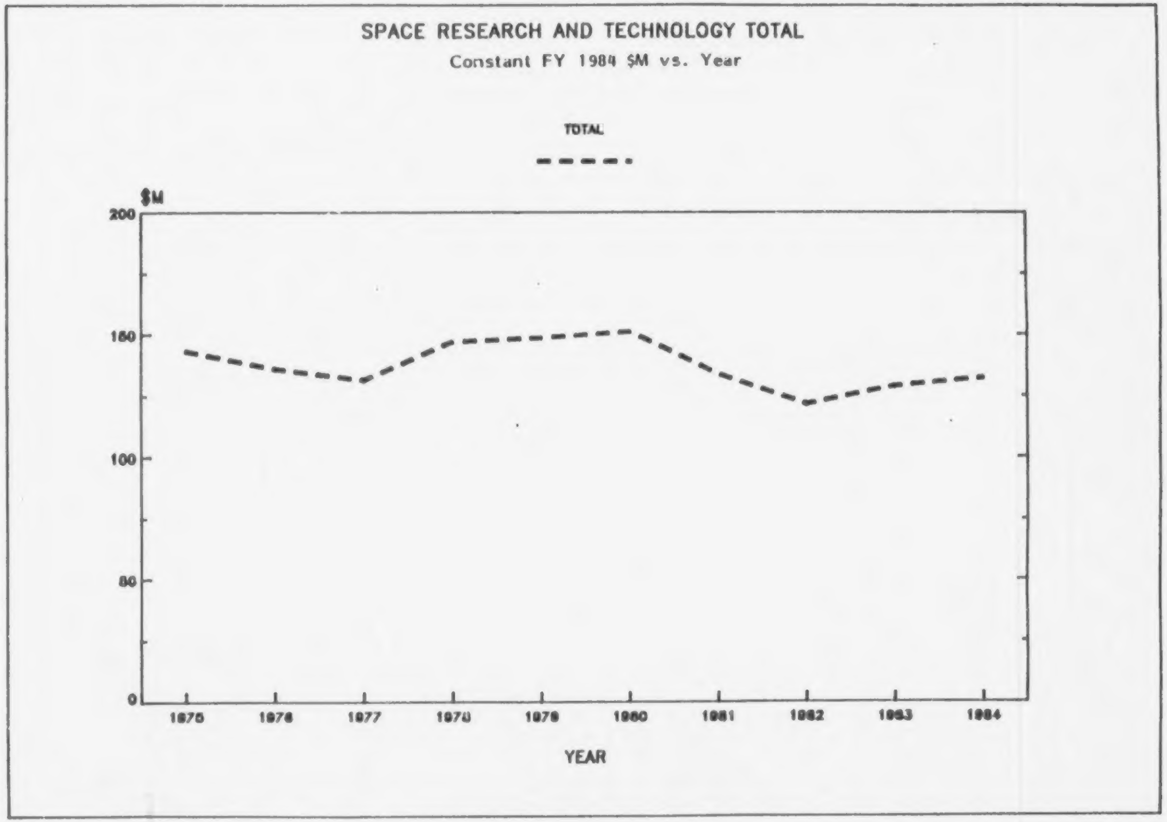
B. Review of the Space Research and Technology Program

The space research and technology program is a broadly based technology development program which addresses the major technology elements involved with spacecraft design and development. Included in the program are activities directed to spacecraft electric power, propulsion, thermal control, structures, data handling, communications, and attitude control. These are long-standing activities within NASA and can be considered generic to any spacecraft program. In addition, there are some activities which address the technologies of spacecraft passing through an atmosphere; these are not generic in nature but are focused more on the needs of a specific mission or a set of specific missions. Aerothermodynamics is one of these mission-specific areas that has applicability to those planetary missions that enter the atmosphere of another celestial body.

In the space research and technology program, the effort spent on generic technologies is appropriately much greater than for mission-specific technologies since the number of missions making use of the generic work is obviously considerably greater than those requiring some specific technology development. However, this Subcommittee questions whether some of the mission-specific technologies are receiving adequate support to enable the SSEC-recommended set of planetary missions.

The ten-year budget history for space research and technology (Figure 2) shows little significant change over the entire period in constant year dollars. The yearly budgets have averaged approximately $135M. This budget history has meant a relatively stable program that has suffered little from the disrupting effects of large swings in funding. The long-standing technology development projects have been able to maintain their continuity and momentum. For the most part, these long-standing projects have appropriately addressed the spacecraft generic technologies.

On the other hand, this constant dollar budget has, since 1982, become a decreasing fraction of the total NASA budget (Figure 3). The subcommittee urges NASA to examine whether a decreasing budget fraction is appropriate for space research and technology when the Agency is embarking on a reinvigorated planetary program that contains a number of mission-specific technology needs. Also, NASA's new initiative on Space Station will clearly place additional technology development requirements on OAST and hence upon OAST's technology budget. Without additional funds, Space-Station-unique technology development will occur at the expense of planetary program mission-specific technology development.



SPACE RESEARCH AND TECHNOLOGY TOTAL

Constant FY 1984 $M vs. Year

FIGURE 2

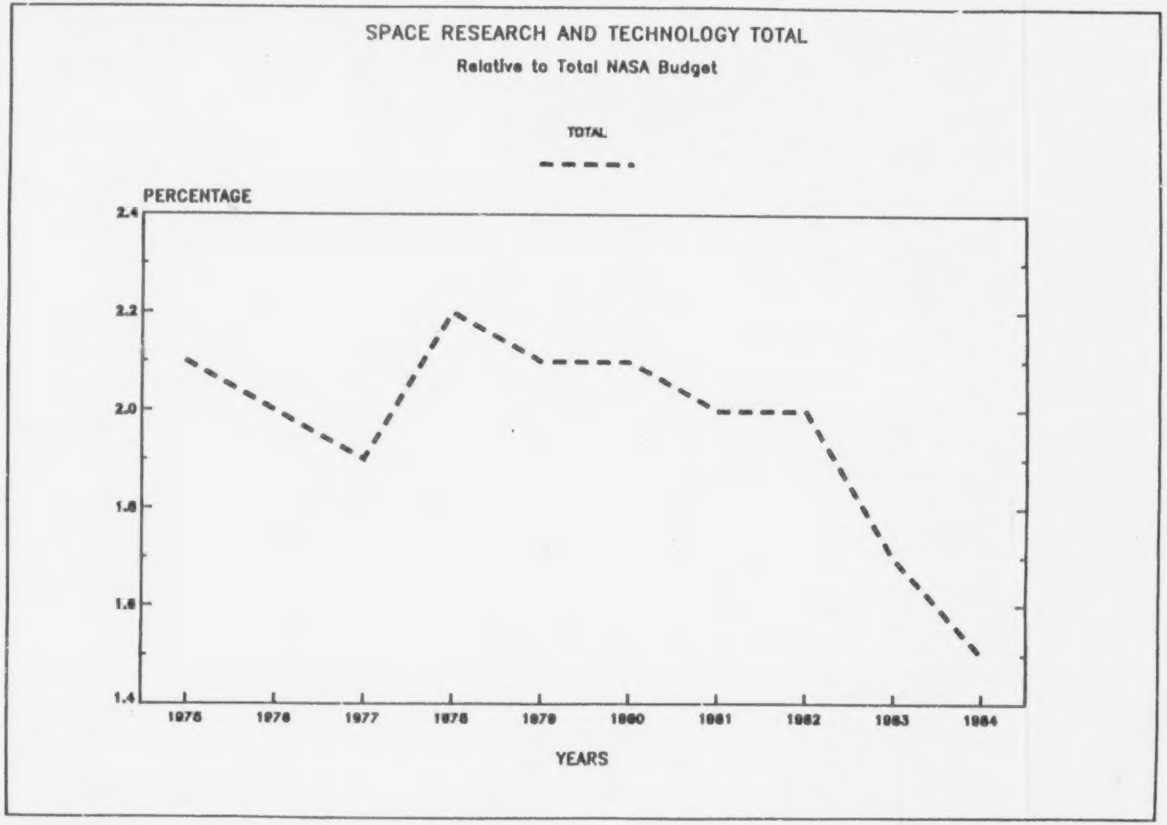

SPACE RESEARCH AND TECHNOLOGY TOTAL
Relative to Total NASA Budget
TOTAL
PERCENTAGE
2.4
2.2
2.0
1.8
1.6
1.4
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
YEARS

FIGURE 3

It appeared to the Subcommittee that the allocation of the space research and technology program budget to the individual discipline areas and the selection of the specific projects within those areas has generally been performed without considering the SSEC-recommended planetary missions. The major missions of NASA such as the Space Transportation System and now the Space Station are providing the general framework for the technology program's definition. The generic spacecraft technologies have been based on supporting a wide variety of conventional missions and, for the most part, also fulfill the generic technology needs of the planetary program. The subcommittee perceives little program planning directed toward the specific technologies needed to enable both the planetary Core and Augmentation missions proposed to start five to ten years hence.

Beyond the recent past, strong collaborative planning activity existed between the planetary mission managers and the research and technology managers. This collaboration has been weak over the last few years primarily due to a lack of new planetary missions and weak prospects for a sustained program. A well defined set of planetary missions with a reasonable chance of being implemented has only recently become available as the result of the SSEC recommendations. The absence of such mission definitions and their associated technology drivers has prevented NASA from developing a technology program to meet the specific needs of the planetary missions. Now that there is a clearly defined solar system exploration program, the process of defining the driving technologies and planning a program to develop them can and should begin.

NASA has recognized this planning need and has begun to take the appropriate actions. A memorandum of understanding currently is being developed between the Office of Space Science and Applications (OSSA) and the Office of Aeronautics and Space Technology (OAST). The memorandum calls for a once-a-year process to define the space science and application programs technology needs and then identify technology development projects to meet those needs. This Subcommittee is highly supportive of such an effort and urges NASA to assure its continuity. The Subcommittee also believes a review of the identified technology drivers by the NASA Advisory Council would aid NASA in its process.

IV. FINDINGS OF THE SUBCOMMITTEE

A. Adequate Areas of Technology Support To Future Planetary Missions

As a result of its review of the space research and technology program, the Subcommittee found that there are a number of areas of the program which currently appear adequate for the future planetary missions defined by the SSEC. These areas all fall in the category of generic spacecraft technology development.

The space research and technology program supports most of the technology needs of the Core missions of the SSEC recommendations and the Subcommittee feels reasonably comfortable with this portion of the program. However, it should be noted that technology adequacy for the Core missions should occur almost by definition -- because the Core missions basically were selected to require only existing technology. This was generally found to be true. Some exceptions were found, primarily in the mission-specific technologies, and will be discussed in the next section.

Three technology areas were found adequate for both the Core and the Augmentation missions: communications, electrical power, and chemical propulsion. While considerable work applicable to the planetary program was found in the areas of aerothermodynamics, materials and structures, controls, and electronics and sensors, specific deficiencies were identified in each of these areas.

The Subcommittee judged that there is fairly good coupling of the NASA and DOD technology activities in several areas and encourages this to continue. However, it should be emphasized that there is little DOD activity associated with either the unique sensing activities for planetary exploration or the problems of planetary/comet landing and sample gathering. In order to get the most from its limited technology resources, NASA must continue to plan and evaluate its program to ensure it is focusing on those technologies not being addressed by the DOD or industry.

B. Deficient Areas of Technology Support To Future Planetary Missions

The Subcommittee has identified a number of technology areas that need to be strengthened to supply proper support for the SSEC-identified list of future planetary missions. The most serious deficiencies are associated with the programs in the Augmentation missions category. The absence of the identified technologies will prevent the Augmentation missions they enable from becoming approved and thus present a self-fulfilling prophesy: the technology is not needed because there will be no mission; and there will be no mission without the needed technology.

The most deficient area appeared to the Subcommittee to be technology for surface/core sampling of various bodies in the solar system. The Core SSEC program has identified missions to sample a comet tail (a high-speed flyby in which comet atoms are ionized and the ions captured on foils) and to analyze the Martian surface in-situ. The most severe deficiencies appear in the Mars Probe/Network mission where new technology related to miniaturized RTG power sources and aerocapture and planetary entry must be developed in order to enable this mission. The Augmentation program includes the technologically demanding Mars Sample Return and Comet Nucleus Sample Return missions. If these missions are ever to be accomplished, the issues of sample acquisition, contamination, sample storage, environmental protection and autonomous operation must be addressed.

The Mars Sample Return mission has several other challenging technology areas that are currently receiving little attention: robotics, rover technology, automated rendezvous, sample transfer, artificial intelligence for adaptive guidance and control and hazard avoidance, aeromaneuvering, aerocapture, and possibly in-situ propellant generation. The ability of the Titan probe to make local measurements at high altitude in the haze layer will require significant advances in aerocapture systems.

The area of autonomous command and control cuts across many missions beyond those involving surface sampling. It is important to both short duration/high activity and long-term/low activity missions. The comet and asteroid rendezvous missions are particularly in need of improved autonomy capability. The Subcommittee sees substantial benefit to future planetary missions by increased emphasis on advanced, high-speed computational techniques and artificial intelligence capability to meet the autonomous command and control needs.

The Mariner Mark II spacecraft needs a number of significant short term and long term developments. The spacecraft will use an all X-band telemetry system and the designs will be greatly enhanced if solid state power amplifiers and new high gain antenna feeds are available. Many other important subsystems which need to be improved or modified were also identified, but it was determined that many of these needs are enhancing rather than enabling so that they did not strictly fall within the guidelines of the Subcommittee's review. In addition, since the Mariner Mark II spacecraft is now in a preliminary design phase, these technology needs are generally near-term and OSSA must bear a major responsibility for the development of such capabilities. The Subcommittee did note that OSSA will have difficulty in supporting these developments for planetary programs because the planetary research and analysis funds have been significantly reduced in the FY 1985 budget.

Although the above, in the Subcommittee's judgment, comprise the most serious deficiencies in technology development to support future planetary missions, there are four additional areas where the Subcommittee believes more attention is required:

1. Long-life batteries for planetary probes and penetrators. One of the areas most constraining the life time of all penetrators and of the probes into dense atmospheres is battery life time. The eventual success of the SSEC's Core program Mars Surface Probe/Network and Saturn Orbiter/Titan Probe missions will depend on the capability of the batteries to support long-term penetrator surface operation and the Titan probe's slow descent through its haze layer.

2. Penetrator technology. Again for the Mars Surface Probe mission, there is additional technology development needed for placing the penetrators where desired (including the proper depth in the regolith) and in insuring survival of their instrumentation and communication systems.

3. CCD Images. The extremely high quality CCDs needed for NASA Core mission and astronomical mission instrumentation are few in number and very expensive to produce; hence, they are not likely to be pursued by industrial manufacturers concentrating on large volume, commercial grade CCDs. NASA needs to support industry by funding the development of custom-tailored CCDs to support NASA-unique requirements. Additional effort is also recommended in Multi-Spectral sensing and spectral analysis.

4. Solar Electric Propulsion implementation. NASA has developed considerable capability in the fundamentals of solar electric propulsion but needs further effort on implementing the technology for specific missions, such as the rendezvous missions that require low-impulse, long-life propulsion.

C. Budget Adequacy

The space research and technology budget appears adequate to conduct NASA's generic research and technology program. The relative constancy of the inflation-adjusted funding over the past ten years is admirable. Yet the recent decrease in the fraction of the total budget devoted to space research and technology concerns the Subcommittee. A continuation of that trend is considered improper for adequately supporting the agency's missions.

While the subcommittee has found several deficiencies in the technology program's support of the Augmentation missions and in some specific areas of the Core planetary missions, it cannot state that the space research and technology budget is inadequate without an in-depth review of all activities to see if there is proper balance across all areas. However, the Subcommittee can say that it found no areas where overfunding was obvious and has strong suspicions that there is inadequate funding to properly address the deficient areas of mission-specific technology. Any further conclusions on the budget's adequacy must be based on more detailed identification of the planetary program's technology drivers, definition of the proper technology development projects and comprehensive review of the ongoing activities.

V. RECOMMENDATIONS

The Subcommittee's recommendations fall in two general categories: 1) the approaches, methodology and interactions used in planning the space research and technology program and 2) the technology activities needing increased emphasis to adequately support the planetary program.

A. Program Planning

In its review of the space research and technology program, the Subcommittee was not able to identify the process NASA uses to plan the various technology efforts and allocate funding to the various areas. The Subcommittee recommends NASA document the procedures used and the interfaces between the mission planners and the technology managers. The Subcommittee understands that the memorandum of understanding being developed between OSSA and OAST is designed to address this issue, but the memorandum does not cover all of the missions for which OAST develops technology. It is, therefore, important to document the process for the complete space research and technology program so that how priorities are set can be understood and, when necessary, modified as NASA's needs and programs change. It is also recommended that the planning process be reviewed by both the Space Systems and Technology Advisory Committee and the Space and Earth Science Advisory Committee of the NASA Advisory Council.

The Subcommittee's strongest recommendation is that the mission-specific technology needs of the SSEC-recommended Core planetary missions and the overall technology needs of the Augmentation missions be identified and evaluated for their proper emphasis in the space research and technology program. The cooperation between OSSA and OAST evidenced by the memorandum of understanding should be fully developed as the means of assuring that technology needs and the breadth of their applicability are well understood. It is likely that all identified technology needs cannot be adequately addressed within the limited space research and technology funding. It is recommended that the highest priority be given to the generic technology areas supporting multiple missions and hence benefiting the broadest parts of NASA. NASA should support those technologies that are peculiar to its missions and not otherwise addressed by the DOD (providing the DOD technology is available to NASA missions) and industry.

The Subcommittee's primary concern is that the technologies needed to enable the planetary Augmentation missions must be developed or those missions will never be approved. While having the needed technology in hand does not guarantee or even compel mission approval, it is necessary to have a technology program that does not by definition exclude the Augmentation missions. Many of the technologies needed for these missions such as robotics, VHSIC, very long-life electronics, improved data compression and information extraction techniques, artificial intelligence and fault tolerance are applicable to a wide range of NASA programs and will provide significant benefits throughout the Agency independent of any particular planetary mission. These technologies should rank high on the listing of areas needing additional emphasis.

B. Needed Technology Activities

The Subcommittee recommends that the cooperative OSSA/OAST process to define the technologies needed for future planetary missions include the following eight areas identified by the Subcommittee in its review: 1) aeromaneuvering and aerocapture with controlled lift, 2) autonomous command/control, 3) surface/core sampling activities, 4) materials and structures, 5) robotics, 6) long-life, small power sources, 7) advanced/adaptive signal data processing, and 8) electric propulsion. In addition, the possibility for in-situ propellant generation offers strong potential for carrying more weight in instrumentation, rather than fuel, and should be investigated along with its associated propulsion system.

Aerocapture is either an enabling or strongly enhancing capability, particularly for the Mars Sample Return mission. Continued work, particularly at the systems level, is needed in proof-of-concept demonstrations as well as early identification of systems level characteristics and problem areas. For materials and structures, additional work is needed in areas such as material science, thermal protection, dimensionally stable composite materials and "smart" mechanisms for positioning devices, docking, and latches.

Autonomous command/control is important to both short duration/high-activity requirements, and long-term lower level operation. Sensors, devices, artificial intelligence, and software are but a few of the specific technologies supporting the needed capabilities. Application to robotics is the most obvious benefit, but automated spacecraft control, rover technology, rendezvous/docking, aerocapture, and sampling are other areas which would benefit from advances in the related technologies.

Sampling activities, while definitely an application of assorted technologies, appears to have little, if any, support in the current generic technology activities. Issues of contamination, acquisition, packaging and environmental protection for a sample of planetary material are key to the design of acceptable sampling systems. Autonomous command and control and fault tolerant computers are technologies that also impact heavily on such remote sampling systems.

Probes for Titan, Uranus, and Neptune require development. For Titan and Mars, entry probe concepts are needed that will be suitable for relatively low speeds and low atmospheric densities. The whole concept of a long-lived instrumented penetrator for the Mars Probe/Network mission is in a rudimentary state. A rugged miniature power source is needed that addresses the issues of thermal compatibility, instrument interface and hardware packaging.

Long life, highly reliable advanced systems require advances in device technology which include VHSIC, GaAs, Surface and Bulk Acoustic devices and radiation sensors. Since the DOD has active programs in these areas, NASA can benefit by coordinating with DOD. The greatest leverage for NASA would be to use these devices for advanced adaptive computational techniques and artificial intelligence. NASA should concentrate on NASA "unique" devices which include extremely long life, complex radiation environments (such as around Jupiter) and very sophisticated one or a few of a kind devices.

Electric propulsion, using either solar or nuclear power, is an enabling technology for the comet sample return mission and can enhance a number of other missions. For high energy missions, it can significantly reduce trip time and/or increase payload. The increased payload capability may be an important need for the success of these demanding missions.

The generation of propellants in-situ on the Martian surface could have high leverage for the Mars Sample Return mission. If this mission is required to carry all the propellant to the Martian surface that is needed to leave it, whether it be from the Earth's surface or a space station, a major fraction of the landed weight will be propellant for lift-off of the return vehicle. With in-situ propellant generation, the mission can concentrate its landed payload on effective sampling apparatus instead of propellant for return. A considerable amount of study and technology development will be necessary to prove the feasibility of this approach and that we indeed can exploit this leverage.

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of: C:JJM:djm

MAR 19 1984

Honorable Harold L. Volkmer
Chairman
Subcommittee of Space Science
  and Applications
Committee on Science
  and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

In the House Authorization Report 98-65, the Committee requested NASA to submit to Congress an annual report on the NASA Materials Processing in Space Program.

I have enclosed the report in compliance with the Committee's request. If you need additional information, please call me.

John F. Murphy
Assistant Administrator for
  Legislative Affairs

Enclosure

MICROGRAVITY SCIENCE AND APPLICATIONS ANNUAL REPORT
TO THE
HOUSE COMMITTEE ON SCIENCE AND TECHNOLOGY

SUMMARY

This report summarizes the activities of the newly formed Microgravity Science and Applications (MSAD) Division in the Office of Space Science and Applications at NASA. This Division was created to focus NASA's microgravity research/programmatic activities in one organization in order to most effectively use and demonstrate the benefits of the microgravity environment of space. The MSAD program content consists of elements of the former Materials Processing in Space Office, OSSA, and the PACE Program, formerly in OAST (Office of Aeronautical and Space Technology). The research base of the total program was reviewed for excellence and with regard to relevance to microgravity studies. Appropriate changes were made in content to reflect the objectives (detailed in this report) of the MSAD requiring quality microgravity science/technical investigations. The report also describes the new advisory committee structure which will be needed to support the expanded technical and programmatic objectives of the Division.

A vigorous Research and Analysis (R&A) Program will continue to be the basis of the science activities of the MSAD and some recent results of this program are described, especially in the areas of: 1) thermal/solutal flows on solidification/crystal growth, 2) convective/sedimentation in electrophoretic systems, and 3) phase separation in immiscible systems. Several microgravity investigations have been flown in the past year using the Space Shuttle. These are described, especially the MLR (Monodisperse Latex Reactor, whose products have been requested by the National Bureau of Standards for use as calibration standards) and the CFES (Continuous Flow Electrophoresis System, which may lead to the first commercial products manufactured in space).

The MSAD will continue to aggressively pursue industrial/commercial partners and jointly develop programs of microgravity investigations which will help accelerate potential commercial applications. The general guidlines for commercial interactions with the MSAD are contained in this report. In addition to those joint agreements already in place (these are detailed in the report), negotiations are being pursued with ALCOA, Minnesota Mining and Manufacturing Company, and the Center for Blood Research, Boston, MA, to develop new agreements.

Plans for the coming year include an expanded R and A program based on quality science and a rationale for microgravity investigations. The flight investigations program using the Shuttle has been expanded by over 100% for the coming year. This report contains an overview of these future plans, including, the overall methodology for determining a University Center of Excellence in Bioprocessing; the Microgravity Science Research Laboratory at the Lewis Research Center, OH; and upgrading PACE projects to microgravity flight status.

Future reports will contain the results of this active and productive year.

MICROGRAVITY SCIENCE AND APPLICATIONS ANNUAL REPORT

I. INTRODUCTION

This report contains a summary of the National Aeronautics and Space Administration (NASA) activities in Microgravity Science and Applications. It is intended to provide an overview of both the flight and research programs with special emphasis on the accomplishments of the past year and plans for the future. Since this is the first annual report, it will also cover the program history and significant results of research done since the inception of the program.

II. GOALS AND OBJECTIVES

The overall goals of the NASA Microgravity Science and Applications Program are:

1) To investigate the behavior of materials and fluids and the effects on processes carried out in the microgravity environment;

2) To provide a better understanding of the effects and limitations imposed by gravity in processes carried out on earth;

3) To evolve processes that exploit the unique characteristics of the microgravity environment of space to accomplish results that cannot be obtained in unit gravity; and,

4) To explore and determine potential applications for commercialization in space.

Near-term goals include expansion of the research base, increase in the awareness of the microgravity program in both industry and academia, broadening commercial and applied activities, and the establishment of a long-range program plan. Near-term use of STS middeck opportunities will be emphasized as well as maximizing the use of NASA's unique ground facilities (droptubes, droptowers, and aircraft). Finally, considerable emphasis will be placed on efforts geared toward influencing the design and planning for the space station to ensure that the unique requirements of Microgravity Science and Applications are accommodated appropriately.

III. PROGRAM OVERVIEW

The Microgravity Science and Applications Program concentrates on the physical sciences, but does not include the study of the effects of gravity on living organisms which is covered by the NASA Life Sciences program. The Microgravity Program is made up of 6 distinct disciplines:

1) Electronic Materials
2) Biotechnology
3) Metals and Alloys
4) Glasses and Ceramics
5) Combustion Science
6) Fluid and Transport Phenomena

Supported research efforts are currently underway at about 30 universities, 9 industrial organizations, 2 non-profit organizations, the National Bureau of Standards, four NASA Centers, and the Jet Propulsion Laboratory. Flight activity has increased dramatically with the operational phase of the Space Transportation System (STS), and is expected to continue to increase. Approximately 18 investigations are planned to be flown in 1984.

NASA is strengthening its program to encourage commercial entities to conduct research in microgravity applications, with an eye towards possible commercialization of appropriate microgravity processes and materials.

IV. PRESENT PROGRAM AND RECENT ACCOMPLISHMENTS

In FY 1983, a new division was formed within the Office of Space Science and Applications. The Microgravity Science and Applications Division (MSAD) includes the activities of the former Materials Processing in Space Office, as well as encompassing physical and chemical processes and phenomena which are affected, or are thought to be affected, by microgravity. New or realigned mechanisms have been put in place to enable increased involvement of both the academic and industrial community, and to advise the Division regarding the relevance of the research tasks underway and what directions should be taken in the future.

The new Division has been working with the Space Applications Board (SAB) of the National Research Council. The Board has been following the early activities of the Division and has, thus far, indicated its satisfaction with its progress as indicated in a letter to Congress dated September 1983. We expect to continue to work with the SAB and to keep it fully appraised of future plans and directions.

The MSAD oversight has been assigned to the newly formed Space Applications Advisory Committee (SAAC). At the request of the MSAD Director, and with the approval of the SAAC, a special subcommittee has been formed to review the MSAD program. It is expected that the subcommittee will directly affect the operations of the MSAD and will substantially contribute to its excellence and growth.

A new working group structure, composed of University and Industry members, has been established by the Division, based on the six microgravity science and applications disciplines (Electronic Materials, Glasses and Ceramics, Fluids and Transport Phenomena, Metals and Alloys, Biotechnology, and Combustion Science). The primary functions of the working groups are to assist the Division by initially documenting the fundamental questions to be addressed within each discipline and, then, assigning a priority ranking to these questions. A long-term program will then be defined. A second, but very important, function of these groups will be to assess progress and recommend changes in the continuing program.

A Division level working group will be established to directly assist the Director in maintaining excellence and discipline balance, as well as suggesting potential new areas of basic and applied research. This group will handle the function of detailed program review and will interact with the Director, the Discipline Working Groups, SAAC, and the NASA Advisory Council.

V. RESEARCH AND ANALYSIS

The NASA Microgravity Program has made significant contributions to the Materials Sciences Community as evidenced by the number of papers published in refereed journals. This number has increased from a few dozen published before 1977 to over 160 published during the past year. Some of the significant results are summarized in the following paragraphs:

ELECTRONIC MATERIALS

The following studies are examples of those sponsored by NASA in the area of crystal growth, a key element in our ability to produce more advanced electronic materials. These and similar studies have contributed significantly to our understanding of crystal growth processes and form the rationale for crystal growth experimentation in space.

Analysis by crystal growers of convective flows and their effect on the growth process has only recently begun. The flows associated with crystal growth are complicated by the fact that most systems of interest have more than one component, hence, both thermal and compositional effects must be considered. Since thermal diffusivity is usually several orders of magnitude larger than chemical diffusivity, the length scales are vastly different. Therefore, it is extremely difficult to model the combined thermal-solutal or double diffusive convection.

Dr. Sam Coriell and co-workers at the National Bureau of Standards (NBS) performed a linear stability analysis on the solidification of a dilute binary system in which the rejected component is less dense than the bulk melt. This creates a potential instability in a vertical, thermally stable Bridgman configuration because of the lower density diffusion layer that builds up just above the solidification interface. Coriell showed that such systems could be unstable, even when the concentration was so low that the combined thermal and solutal effect produces a density that decreases montonically with height.

The effects of thermal convection on the radial segregation of dopants in crystal growth by the Bridgman technique were studied by Dr. Robert Brown, Massachusetts Institute of Technology (MIT) using finite element analysis. Brown was able to include the growth interface as a free boundary condition in the problem. He showed that even in vertical geometries with hot over cold, which were thought to be stable against thermal convection, considerable convection occurs because of radial gradients which are impossible to avoid. He also showed that even a very small convective flow could significantly affect the radial distribution of dopants.

Dr. Franz Rosenberger, University of Utah, has extensively analyzed convection in closed tube vapor crystal growth and found that viscous interactions between the transporting vapor and the container wall create density gradients that are always convectively destabilizing; hence, it is not possible to achieve diffusion-controlled vapor transport in a gravity field. Further, he found that the accepted models for diffusional vapor transport work as well as they do only because they contain self-cancelling errors.

PHASE SEPARATION MECHANISMS

Early attempts to avoid phase separation from density differences in the solidification of monotectic alloys (systems that have liquid phase miscibility gaps) in a microgravity environment indicated that other phase separation mechanisms that do not involve gravity are also important. Recent work on model organic systems that are transparent and can be made almost neutrally buoyant has revealed some interesting insights into some of the mechanisms. Dr. John Cahn (NBS) showed in 1979 that such systems would be unstable if the minority phase wet the container in preference to the majority phase. A competing process works to drive the minority phase opposite to the direction of heat flow, usually away from the outer surface.

Understanding such mechanisms may allow us to control phase separation in such systems and produce fine in situ dispersions in some of the large number of binary systems that have liquid phase miscibility gaps.

CONTAINERLESS PROCESSING

Since liquids, especially high temperature melts, can be contained solely by their surface tension and positioned in a microgravity environment by small non-contacting forces provided by electrostatic, electromagnetic, or acoustic fields, there are a number of potential applications for containerless processing in space.

Containerless processing is possible in a limited fashion on the ground using drop facilities, aircraft, and/or various levitation techniques. Drop tubes are now operational at the Marshall Space Flight Center (MSFC) and the Lewis Research Center (LeRC). Considerable work has been done with the superconducting niobium alloys. Undercoolings in excess of 700°C have been observed. Metastable phases have been produced in bulk specimens by a combination of deep undercooling and oil quenching. A variety of smaller drop tubes are in operation at the Jet Propultion Laboratory (JPL) to study the formation of liquid shells and the mechanisms that cause the interior gas bubble to become centered in the liquid shell.

An electromagnetic levitation facility has been developed at General Electric, Valley Force for the study of high temperature thermophysical properties of tungsten and other refractory materials. A small levitator originally developed for the Space Processing Applications Rocket (SPAR) program has been modified to perform similar experiments on the Space Shuttle.

Air-jet levitators are in operation at Yale University and at MSFC. The levitator at Yale is being used to develop new measuring techniques using laser-induced fluorescence. The device at MSFC is used in conjunction with a powerful CO_2 laser to melt small samples of various oxides to study glass formation. Samples have been heated in excess of 2000°C in this facility.

Major work has been done on levitation technology at JPL. Techniques for positioning and rotating samples using acoustic fields (suitable for samples to be processed in a gaseous environment) and electrostatic fields (for processing in vacuum) have been developed and extensively tested in KC-135 aircraft and SPAR rocket flights. A 3-axis acoustic levitator furnace is being developed for use on the Space Shuttle.

BIOTECHNOLOGY

Considerable progress has been made in understanding the various flows in continuous flow electrophoresis and the limitations imposed by operating such devices in earth's gravity. Analysis by Dr. Dudley Saville, Princeton University, indicates that unstable convection in such a device can occur at Rayleigh numbers as low as 6 (as opposed to ~1600 for a static column). It was also found that minute temperature variations across the width of the chamber can produce cross-flows that result in sample stream meandering and loss of resolution.

A novel concept for eliminating sample stream distortion from Poiseulle flow has been developed by Mr. Percy Rhodes (MSFC). The walls of the device are endless belts that move with the fluid. This allows the sample stream to occupy the total width of the chamber without loss of resolution from wall effects.

VI. FLIGHT PROGRAM

MIDDECK EXPERIMENTS

Shortly after the first Shuttle flight, the Microgravity Science and Applications program was able to resume long duration experiments in a microgravity environment. The first experiments were carried out in the Middeck of STS-3 in March 1982.

Monodisperse Latex Reactor

A series of seeded polymerization experiments beginning with STS-3 are being conducted by Dr. John Vanderhoff, Lehigh University. The objective of this series of experiments is to produce precision polystyrene spheres with uniform sizes for a variety of applications. When this effort was initiated, precision-sized spheres, produced on earth in the 2-40 micrometer range were not available in quantity, were not spherical and had a size dispersion of about 3%.

The particles produced by Dr. Vanderhoff on the Space Shuttle have size dispersions generally less than 1% and appear to be perfectly spherical, as verified by independent analysis by the NBS. In fact, the NBS has determined that these particles qualify as standards and has requested additional samples for this purpose.

Continuous Flow Electrophoresis System (CFES)

A series of flight investigations were flown using the Continuous Flow Electrophoresis System (CFES) developed and built by McDonnell Douglas Astronautics Company (MDAC) under the terms of a Joint Endeavor Agreement (JEA). The experiments started on STS-4 and are primarily to determine the technical advantages of CFES operation in microgravity and to assess the commercial viability of CFES separations of pharmaceuticals in space. The results of experiments conducted by MDAC to date have been very encouraging. The flight data apparently show that operation in space can obtain up to 700 times the throughput and purity for the separations of "proprietary" biomaterial. MDAC is proceeding with their flight program which may ultimately lead to commercial processing in space.

As part of this JEA, NASA-sponsored investigators have had a chance to conduct 8 separations on the CFES to help understand generic questions on electrophoretic separations in space. Material that was separated includes hemoglobin, polysaccharide, and kidney cells. These results are still being analyzed.

Materials Experiment Assembly (MEA) Experiments

The MEA is a carrier for materials processing experiments and can accommodate up to four Space Processing Applications Rockets (SPAR) type experiment packages. The MEA provides power, data acquisition, thermal control, and heat rejection for the experiments independently of the Shuttle. This vastly simplifies the integration with the orbiter and allows the program to take advantage of more flight opportunities. The MEA was first flown as part of the OSTA-2 payload on STS-7, and performed flawlessly.

Two experiments involving a total of 6 samples were flown in two General Purpose Rocket Furnaces (GPRF's). One furnace was configured for isothermal processing and the other configured for gradient processing. The furnaces functioned properly and produced the required thermal profiles in the samples.

Dr. Stanley Gelles, S. H. Gelles Associates, flew several monotectic alloys similar to those flown earlier on sounding rockets except the crucible materials were chosen to avoid phase separation from critical wetting. One sample was processed in the gradient furnace to examine the effects of thermal migration of the minority phase droplets driven by thermal capillary flows. Other samples, processed in the isothermal facility, had plungers to eliminate free surfaces and possible surface tension driven flows. The samples are presently being analyzed.

Dr. Heribert Wiedemeier, Rensselaer Polytechnic Institute, repeated his earlier Skylab experiment involving vapor crystal growth of Germanium Selenide (Ge Se) except that an inert gas was substituted for the iodine transport gas used previously. The purpose was to determine if the previously observed anomalous transport rates were, in fact, caused by chemical reactions throughout the growth ampoule, or whether other mechanisms must be sought. Although these results are not yet available, one unexpected result was observed. The crystals grown in space were almost an order of magnitude larger than those grown under identical thermal conditions on the ground. Very well-defined platelets, some as large as 5X10 millimeters, grew in an open web-like structure in the flight ampoules. The ground control ampoules contained a crust of very small crystallite or poly-crystalline material in the growth region. Apparently, the effects of small gravity driven flows in the vicinity of a growing crystal are more pronounced than anyone anticipated.

A single-axis acoustic levitator (SAAL) furnace with an automatic sample exchange mechanism containing 8 samples was also flown on MEA. The purpose of the experiment was to test the levitation capability of this device at high temperatures (up to 1600°C) and to explore containerless glass formation. A mechanical malfunction occurred during the processing of the third sample involving the cooling shroud. The camera, which was to have recorded the behavior of the sample in the levitator during processing, also malfunctioned and no data were returned from the experiment. The equipment is being repaired and will be reflown in 1984.

VII. PROGRAM PLAN FOR UPCOMING YEAR

NASA plans to continue the strong research base established during the last several years, and to carry out a vigorous flight investigation program to delineate the potentials and limitations of the microgravity environment for scientific and industrial use. Since the merits of using this environment will ultimately be determined by the participating investigators, strenuous efforts are being made to involve potential users in this demonstration phase.

RESEARCH AND ANALYSIS PROGRAM

The fact that experiments in a microgravity environment can produce new and unexpected scientific results has been established. For example, the anomalous growth rates and large size crystals observed by Wiedemeier have led to substantial reevaluation of transport theory in vapor crystal growth. Undoubtedly, there will be other surprises as the flight program accelerates.

These early results have intensified interest in certain aspects of the program which will be emphasized during the next several years. The areas are described more fully in the following paragraphs.

Single crystals of various electronic materials are extremely important in an area of rapidly expanding technology and may have sufficient value per unit mass to be candidates for a viable commercial endeavor. Furthermore, a strong rationale has been developed in recent years for growing crystals in space. From results mentioned in the previous section, it is becoming increasingly clear that it is virtually impossible to avoid convective effects in crystal growth in unit gravity and that even small flows can result in profound differences in growth morphology, compositional homogeneity, and structural perfection.

Metals and Alloys

Previous low-gravity experiments in the solidification of various alloys and composites have revealed some unexpected and interesting effects. Several nongravitational phase separation mechanisms were discovered in monotectic systems. Much finer rod diameters and spacings were discovered by Dr. David Larson, et al, Grumman Aerospace Corporation, in manganese bismuth/bismuth eutectic directionally solidified in space than were expected from ground control experiments and the theory of convection growth. Dr. Mary H. Johnston, NASA/MSFC, has observed an unexpected difference in dendrite arm spacing in both transparent model systems (ammonia hydroxide) and binary metallic alloys (lead tin and copper aluminum) solidified in space compared to the ground control experiments. Such effects will cause reevaluation of the role of convection in present theories of solidification and will be the object of future flight experiments.

Successful droptube demonstrations have showed that substantial undercooling can be achieved in bulk samples, and that unique metastable or amorphous microstructures can be produced in this manner. It can be expected that a number of space experiments will be encouraged to extend this type of research to materials that cannot be solidified in the droptube. Also, containerless positioning of high temperature melts offers unique opportunities to measure high temperature thermal physical properties of materials, especially those that are highly corrosive in the melt.

Glass and Ceramics

The absence of container walls offers the possibility of avoiding heterogeneous nucleation and extending the range of glass formation to systems that do not readily form glasses. Extreme purity can be obtained by eliminating trace crucible contaminants, especially in gel-derived systems. Some degree of manipulation is also possible by shaping the non-contacting force fields to form various configurations such as precision glass shells, optical fibers, etc. There is considerable commercial interest in very low-loss optical fibers formed from various halide glasses that transmit in the near infrared. Since 100 km of 100 micron diameter optical fiber has a mass of only a few kilograms, fibers with unique optical properties may also be a potential commercially viable space product.

Biotechnology

The McDonnell Douglas Corporation, under a Joint Endeavor Agreement with NASA, has convincingly demonstrated the advantages of performing continuous flow electrophoretic separations in a microgravity environment. Several orders of magnitude improvement in throughput and factors of 4-5 in resolution have been achieved. Similar benefits may accrue in other separation processes, e.g., moving wall electrophoresis, isoelectric focusing, isotachophoresis, photophoresis, thermophoresis, and phase partitioning. There is also interest in unique separations that can be performed in such devices as well as effects that may be caused by the high sample concentrations permitted by microgravity operation. Possible effects include particle-particle interactions during separation, electric field distortions caused by electrical conductivity mismatch between sample and buffer, etc.

Sixteen major universities to date have expressed interest in acting as host for a University Center for Bioprocessing. The Microgravity Science and Applications Division is working with the Space Applications Board, the Pharmaceutical Manufacturers Association, and the University Space Research Association (USRA) to establish a review group, which will recommend selection criteria to NASA, and, after proposals are received in response to NASA's notice of opportunity, will support NASA in review of the proposals. The notice of opportunity is planned to be released in March of 1984, and selection by NASA is currently planned for mid-summer.

Fluid and Transport Phenomena

The elimination of buoyancy driven convection and sedimentation offers the possibility of studying a number of fluid and transport phenomena that are difficult to study in a gravitational field. Examples are 3-dimensional rotating flow, two phase flows, thermocapillary flows, drop dynamics, bubble and droplet migration in thermal and solutal gradients, equilibria configurations in partially filled containers, critical wetting and spreading, nucleation and growth studies, foam stability, rheological studies, and critical phase transitions.

The microscale processes which occur in the atmosphere--aerosol formation by gas to particle conversion and their mechanisms, cloud droplet nucleation and growth, collision-coalescence, ice crystal nucleation and growth, riming, charge separation, precipitation formation, droplet breakup, aerosol scavenging--are among the most difficult physical processes to study experimentally because of the small energies involved and the care which must be exercised to prevent foreign influences from altering the experimental results. The elimination of convective air motions and droplet sedimentation can lead to greatly improved experiment performance due to the isolation from the disturbing influences of chamber walls and other surfaces. The absence of convection also implies that temperature and vapor fields within a gas are controlled only by conduction and diffusion mechanisms which can be accurately modeled; therefore, the unpredictable experimental variations caused by eddy motions are eliminated. Fundamental microgravity experiments which lead to greater or more precise understanding of the important processes in atmospheric cloud microphysics will be encouraged.

COMBUSTION SCIENCE

The absence of a significant gravity field facilitates observations of fundamental combustion mechanisms that might be obscurred under normal gravity conditions by buoyancy driven convection. Our understanding of combustion processes in traditional terrestrial systems (based on theoretical 0-G conditions) can be enhanced by these studies as the data obtained can be compared to analytical predictions of models with gravity controlled terms removed. The microgravity experimental techniques include the ability to uniformly distribute particulate fuels which will not suffer any gravity induced settling, and the burning of a fuel mass which is both motionless and mechanically and thermally isolated. Combustion Science has, for the first time, the opportunity to at last test its fundamental theories.

MICROGRAVITY SCIENCES RESEARCH LAB

The NASA Lewis Research Center (LeRC) in Cleveland, Ohio, has proposed the use of a portion of an existing facility to create a laboratory in materials research. LeRC is currently active in both basic and applied research and the Cleveland location is easily accessible to a large portion of the midwestern University and Industrial community. The Lab will be phased so as to provide a continuing check of usage and utility before major expenditure. In addition to being a valuable facility for ground-based collaborative research, it will also serve as the cornerstone for Microgravity Science and Applications planning for the Space Station requirements.

GROUND FACILITIES

A number of methods have been developed by which low-gravity materials research and materials processing research can be conveniently performed. Research is continuing through use of the droptube, droptower, and aircraft where short duration (seconds to minutes) is satisfactory. Appendix A lists the U.S. Low-gravity research facilities.

FLIGHT PROGRAM

With the Space Shuttle, frequent and long term materials processing activities will be possible. Table 1 lists the processing equipment that is presently available and that is presently planned for this future activity. Table 2 lists the apparatus being used on the Shuttle Middeck and being used or planned for the Shuttle cargo bay. Other processing systems and apparatus will be defined and developed as required to support experiments to be solicited by means of a "Dear Colleague" letter. Other small systems will be developed that take advantage of space and so may have frequent flight opportunities.

The Spacelab facility that occupies the Shuttle's payload bay on some flights will provide support for advanced, sophisticated processing systems.

The current emphasis is on apparatus and experiments for installation on the Shuttle Middeck area with potential upgrading to fly in the orbiter bay or in Spacelab. As information is obtained from these experiments, it is anticipated that the need for greater processing times and higher power will be identified. NASA can envision that a materials processing carrier such as Leasecraft, EURECA, or NASA-provided platforms and/or a Space Station laboratory will be required. This mode of flight will provide a continuous, low-gravity environment, free of Shuttle constraints in mission duration, power availability, and disturbances to the required micro-gravity levels.

PHYSICS AND CHEMISTRY EXPERIMENTS IN SPACE (PACE)

Beginning in FY 1984, the Microgravity Science and Applications Division assumed responsibility for the Physics and Chemistry Experiments (PACE) program, after it had undergone an extensive peer science review. This program promotes and facilitates the utilization of space as a laboratory in which to perform research in the areas of physics and chemistry. Fourteen experiments were selected from the peer science review to continue development of the conceptual design. These 14 experiments include investigations of surface tension phenomena, transport properties of materials near the critical points, combustion phenomena, and relativity. As each experiment completes its conceptual design, another peer review covering science, technical, and programatics will be held prior to committing it to flight hardware development. It is expected that 5 experiments will complete their conceptual design and be reviewed in the current fiscal year. To date, 2 experiments have been reviewed and are beginning flight development.

Commercial Applications

As the material science base develops, there will evolve processes that may form a basis for commercial application. Industry, specifically non-aerospace industry, must be made aware of the research being conducted and encouraged to participate in it. The methods for achieving this are to: 1) create awareness of NASA's research activities and results through publications, seminars, visits of NASA scientists to industry R&D centers, and visits by industry scientists to NASA Centers; 2) encourage industry participation in joint research programs with NASA scientists; and 3) encourage private sector participation in space processing by utilizing Joint Endeavor Agreements, Technical Exchange Agreements, and Memoranda of Understanding (See Appendix B).

Existing NASA facilities for materials research and development, i.e., droptubes, droptowers, aircraft, rockets, and the Shuttle are currently being used by industry to explore research areas of unique interest which may develop into commercial opportunities. The Space Station, when it becomes available, will be used in a like manner. In encouraging the use of these NASA facilities by industry, NASA is in a period which is somewhat analogous to that of the NACA when it assisted a fledgling aircraft industry by providing wind tunnels and technical advice without direct financial assistance.

To acquaint industry with the research results that have been accumulated to date from the experiments conducted in micro-g, a movie film will soon be available that will be shown to a wide industrial audience. In addition, the outreach effort has resulted in a Memorandum of Understanding (MOU) with the 3M Company to explore the possibility for a joint venture. Active research will shortly begin with ALCOA and the Center for Blood Research. These are examples of ongoing user development programs which are attracting industry interest in the use of space.

Appendix A - U. S. LOW GRAVITY RESEARCH FACILITIES

FACILITY	MODE OF ACCOMMODATION	LOW-G-TIME	TYPICAL SAMPLE SIZE*
Drop Tube	Sample Dropped in Evacuated and/or Backfilled to Provide for Supercooling	4.5 sec	1 mm to 5mm Dia.
Drop Tower	Processing System Dropped in Tower	4.5 sec	5 mm Dia. x 8 mm Long
Aircraft			
-KC-135	Parobolic Trajectory Flown with Processing System Aboard	15-25 sec. (Repeats per Flight)	20 mm Dia. x 8 mm Long
-F-104	Parobolic Trajectory Flown with Processing System Aboard	30-60 sec. (Repeats per Flight)	20 mm Dia. x 8 mm Long
Rockets	Parobolic Trajectory Flight Path with Processing System Aboard	4-6 mins	20 mm Dia. x 8 cm Long
Shuttle			
-Middeck	Demonstration Processor (1 kW Typical)	1-7 Days (Thru 1987)	1 cm Dia. x 5 cm Long
-Cargo Bay	Demonstration and Production Prototype Processing Systems (1360 W Typical)	1-7 Days (Thru 1987)	As Required
Free Flyer Carrier (Under Study)	Production Processing Systems (12 kW Anticipated)	As Required	As Required

*Specific sample size dependent upon experiment apparatus size, weight, heat flow conditions, and low-G time.

Appendix B

Joint Endeavor and Technical Exchange Agreement Activity Status

McDonnell Douglas Astronautics Co. - St. Louis, Missouri

o Joint Endeavor Agreement signed January 25, 1980

o Will use MDAC-developed continuous flow electrophoresis equipment to process pharmaceutical materials

o Agreement expires in 1986

o The first four flights for MDAC were highly successful indicating that commercial production of pharmaceutical materials is possible in space.

Microgravity Research Associates, Inc., Coral Gables, Florida

o JEA signed April 11, 1983

o Plan is to make semiconductor materials having electronics applications by a specific crystal growth process under low-g conditions.

Honeywell, Inc., Lexington, Massachusetts

o TEA signed February 24, 2983

o Exchange of technical data and evaluation of processing of mercury-cadmium-telluride crystals (HgCdTe) in low-gravity.

Deere and Co., Moline, Illinois

o TEA signed June 29, 1981

o Explore properties basic to casting process

DuPont, Wilmington, Delaware

o TEA signed June 27, 1982

o Explore catalytic properties of certain alloys

INCO Research and Development Center, Inc., Suffern, NY

- TEA signed January 28, 1982
- Explore electroplating process at low-g

TABLE 1 U.S. MATERIALS PROCESSING SYSTEMS

PROCESSING SYSTEMS	AVAILABILITY FOR ROCKETS & AIRCRAFT	FOR SHUTTLE & SPACELAB	FOR FREE FLYERS
Fluids Experiment System	Ready Now	In Development (1984)	
Vapor Crystal Growth System		In Development (1984)	
Float Zone Experiment System	Planned	Planned	Planned (1988)
High Gradient Furnace System	Ready Now	In Development	Planned (1988)
Acoustic Containerless Experiment System	Ready Now	Planned (1987)	Planned (1988)
Electromagnetic Containerless Processing System	Ready Now		Planned (1986)
Bioprocessing Experiment System		Planned (1985)	Planned (1989)

TABLE 2 U.S. MATERIALS PROCESSING INSTRUMENTS

APPARATUS	SHUTTLE LOCATION/CARRIER	AVAILABILITY
Directional Solidification Furnace (DSF)	Mid-deck	Ready Now
Isoelectric Focusing Experiment (IEF)	Mid-deck	Ready Now
Acoustic Containerless Experiment System (ACES)	Mid-deck	Ready Now
Electrophoresis Equipment Verification Test (EEVT)	Mid-deck	Ready Now
Continuous Flow Electrophoresis System (CFES)	Mid-deck	Ready Now
Monodisperse Latex Reactor System (MLRS)	Mid-deck	Ready Now
Droplet Combustion Experiment (DCE)	Mid-deck	Planned (1986)
Particle Cloud Combustion Experiment (PCCE)	Mid-deck	Planned (1986)
Single Axis Acoustic Levitator (SAAL)	Orbiter/Materials Experiment Assy (MEA)	Ready Now
General Purpose Furnace #1 (Isothermal) [GPRF #1]	Orbiter/Materials Experiment Assy (MEA)	Ready Now
General Purpose Furnace #2 (Gradient) [GPRF #2]	Orbiter/Materials Experiment Assy (MEA)	Ready Now
General Purpose Furnace #3 (Gradient) [GPRF #3]	Orbiter/Materials Experiment Assy (MEA)	Ready Now
General Purpose Furnace #4 (Gradient) [GPRF #4]	Orbiter/Materials Experiment Assy (MEA)	Ready Now
Single Axis Acoustic Levitator-II (SAAL-II)	Orbiter/Materials Science Laboratory (MSL)	Planned (1984)

ALTERNATIVES FOR CONDUCTING NASA'S AERONAUTICAL RESEARCH AND TECHNOLOGY PROGRAM

NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of C:LVN:mdd

OCT 20 1983

Honorable Don Fuqua
Chairman
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As requested in the FY 1984 House Authorization Report 98-65, NASA has reviewed the alternatives for conducting the aeronautical research and technology program. NASA decided to take advantage of the country's economic situation and low rate of hiring by the private sector by proceeding with an aggressive campaign to hire high quality S&E recent graduates. These prospective hires included scientists and engineers with B.S., M.S., or Ph.D. degrees.

The NASA research centers, where approximately 98 percent of the aeronautical research and technology program is technically managed, collectively sent out 484 offers. As of August 31, 1983, the centers had received 282 acceptances or 58 percent of the offers, including 93 female and minority candidates. Of the 282 acceptances, 157 S&E new hires were assigned to aeronautical research and technology organizations.

The research centers were able to achieve this increase in their civil service staff because of the realignment of personnel ceilings among other organizational elements within the Agency. For FY 1984, the research centers Full Time Equivalent ceiling has been increased to accommodate the FY 1983 hires. With the Administrator's emphasis on Reform 88 and increasing productivity in the public sector, we are reexamining the way that we do business within NASA, the deployment of our civil service, and the amount of time the S&E researchers spend on administrative or nonresearch tasks. Our goal is to maximize the amount of time spent on research, thereby increasing our productivity.

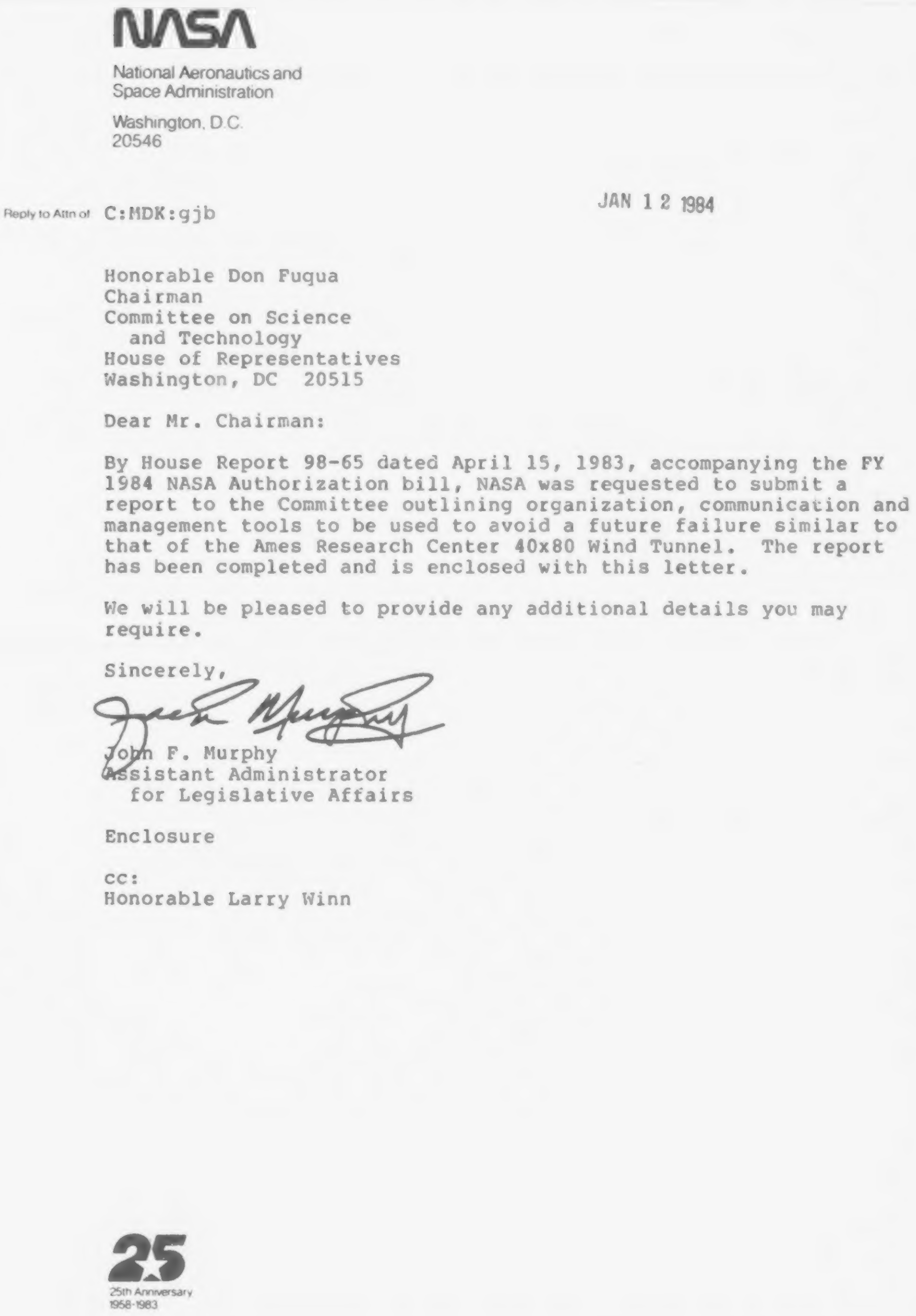
Our response to this Congressional charge, therefore, is twofold--we have increased the number of aeronautical researchers and we are increasing the amount of time available to conduct research.

Sincerely,

Jack Murphy

John F. Murphy
Assistant Administrator
for Legislative Affairs

cc:
Honorable Harold L. Volkmer



NASA

National Aeronautics and
Space Administration

Washington, D.C.
20546

Reply to Attn of C:MDK:gjb

JAN 12 1984

Honorable Don Fuqua
Chairman
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

By House Report 98-65 dated April 15, 1983, accompanying the FY 1984 NASA Authorization bill, NASA was requested to submit a report to the Committee outlining organization, communication and management tools to be used to avoid a future failure similar to that of the Ames Research Center 40x80 Wind Tunnel. The report has been completed and is enclosed with this letter.

We will be pleased to provide any additional details you may require.

Sincerely,

John F. Murphy
Assistant Administrator
for Legislative Affairs

Enclosure

cc:
Honorable Larry Winn

25
25th Anniversary
1958-1983

NASA REPORT ON

40X80 WIND TUNNEL ACCIDENT INVESTIGATION

This report has been prepared in response to the FY 1984 House Authorization Report 98-65 (April 15, 1983). In the report NASA is requested to describe the steps being taken to avoid a future structural facility failure such as that of the 40X80 Wind Tunnel. Particularly, NASA is requested to discuss the "organization, communication, and management tools to be used."

This document addresses the 40X80 Wind Tunnel Accident Investigation Board's recommendations for management actions. A description of NASA's analysis of its facilities design and construction procedures, based on the Accident Investigation Board's recommendations, is provided. Improved management initiatives are then described in detail. The initiatives include revised and reemphasized management procedures and dissemination of the Accident Investigation Board's findings and related lessons learned. Also included in this report are observations on a NASA reorganization and its affect on responsibiliities for facility program development and execution.

BACKGROUND

On December 9, 1982, an accident occurred in the 40X80-Foot Subsonic Wind Tunnel at NASA's Ames Research Center while systems tests in the 80X120-Foot configuration were being conducted. At approximately 93 knots during the 12th operational test and checkout run of the new leg, a large set of moveable turning vanes located directly upstream of the six main drive fan motors collapsed, and was partially ingested into the fan system. The obvious damage observed at that time was the destruction of all 90 fan blades (15 blades per drive unit), damage to the nose cones and stator blades of all six drive motor units, and some minor damage to the tunnel shell and downstream vanes.

CAUSE OF THE ACCIDENT

An Accident Investigation Board (AIB) convened on December 10, 1982. Their final report was published March 15, 1983[1]. The AIB found the most probable cause of the accident to be excessive tensile loading of the moveable vane linkage system for Vane Set 5. This vane set is located immediately upstream of the tunnel's main drive motors, and was designed as a moveable vane to turn the test stream air directly into the main drive motors from either the 40X80 or 80X120-foot test sections of the wind tunnel. The excessive tensile loading caused slippage of the links, which led to rupture of the linkage system. Subsequently, the moveable vanes of Vane Set 5 closed. This blocked the tunnel airflow. Vane Set 5 was overloaded and collapsed. Furthermore, it was determined that the accident occurred through a combination of analyses that underestimated aerodynamic loads, insufficient third party reviews of final designs, inadequate construction quality control and inspection, and deficient configuration control and testing procedures.

ACCIDENT INVESTIGATION BOARD (AIB) RECOMMENDATIONS

The Board's findings covered in detail the technical aspects of the accident. It also addressed those management aspects in which an accident situation was possibly permitted to develop or allowed to exist. The findings and recommendations were used to develop the detailed procedures being followed by the management team now responsible for repairing the 40X80 Wind Tunnel. In addition, NASA management is using the same recommendations as a basis for reviewing the Agency's overall facilities construction management procedures.

The AIB's 17 recommendations can be grouped into three major categories; design and construction considerations, design documentation and change order controls, and operations safety. The first two categories are discussed below in general terms. The third is outside the scope of this report; however, these recommendations were also fully accepted and are being implemented. For a more detailed summary of the recommendations, please see Appendix 1.

oo DESIGN AND CONSTRUCTION RECOMMENDATIONS

The AIB urged a detailed examination for latent damage to the wind tunnel components, and a detailed evaluation of all major tunnel components to insure that the existing construction is suitable for the greater aerodynamics loads imposed by the repowering of the wind tunnel fans. The AIB noted that specific load parameters were largely indeterminate and therefore high safety factors should be used in the design; that all reasonable physical and mathematical tools should be used for design development, and aerodynamic testing should be conducted on models of the various tunnel components. The AIB recommended extensive failure analysis be conducted during design, impartial third party review of designs, and adequate inspection of construction.

oo DESIGN DOCUMENTATION AND CHANGE ORDER CONTROL RECOMMENDATIONS

The AIB stressed the need to formally review and approve all requested design changes before implementing changes. This provides a forum to insure that the change is required and that the design solution is correct and is properly integrated. They noted that all changes to design parameters, form, fit, and function must be completely documented, and contract documents must be kept completely up to date.

ANALYSIS OF PROCEDURES

As mentioned earlier, the NASA facilities community has used the 40X80 Wind Tunnel Accident Investigation Board's recommendations as a "spring board" for reviewing the Agency's design and construction procedures. The planning, organizing, activating, and controlling procedures used in management of NASA's facilities engineering projects have been examined to insure that the procedures do not permit an unacceptable risk environment to occur. Review is still underway by facilities personnel to insure that maximum use is made of the AIB recommendations in order to strengthen facility procedures.

IMPROVED FACILITY PROGRAM MANAGEMENT PROCEDURES

The examination of facility project management procedures has led to positive actions and observations. It must be pointed out in the strongest terms that the comments below do not imply an across the board failure of any NASA center to follow sound facility construction and operation procedures. Rather, the effect of the examination and improvement of procedures has been a reaffirmation and reemphasis of sound procedures and practices.

oo DISSEMINATION OF LESSONS LEARNED FROM 40X80 WIND TUNNEL ACCIDENT

The 40X80 Wind Tunnel AIB report was produced in videotape and distributed to all NASA centers. It has been widely viewed by the facilities engineering community and by operators of research facilities. The purpose is to make people aware of the AIB findings and recommendations, give them an insight into procedural causes that contributed to the accident, and to precipitate reviews of implementing procedures used at each Center. In addition, the chairman of the AIB made a comprehensive presentation on the findings, recommendations, and lessons learned to the principal members of the NASA facilities engineering community at a NASA-wide conference in October 1983.

oo SAFETY

The 40X80 Wind Tunnel Accident and the Board's recommendations led to a complete safety inspection of all Agency wind tunnels and a re-emphasis on inspection and repair of high pressure air and gas systems, which was already underway. For example, Langley, Marshall, and the National Space Technology Laboratory have high pressure gas repair projects proposed in current budgets as a result of these inspections. Ames has scheduled wind tunnel drive motor repair projects that were programmed as a result of detailed safety inspections of drive systems.

Safety procedures have been reviewed and revised or re-emphasized where necessary. These procedures define "red line" limits for wind tunnel operating parameters, and call for termination of tests when "red line" limits are exceeded or where operating anomalies are noted.

All new or modified facilities with high energy sources, such as wind tunnels, will receive single point failure analyses and failure modes and effects analyses prior to being operated. Safety analyses of facilities with high energy sources will be made a design requirement in an upcoming revision of NASA's facilities implementation instructions. In the interim, emphasis on the requirement has been given by means of dissemination of the 40X80 Wind Tunnel Accident Review Board videotape.

oo DESIGN REVIEW PROCEDURES

Although the procedures for a third party design review system have been in place and are routinely used, third party review of designs of very technical or high risk structures is receiving renewed emphasis. If designed by an engineering firm, for example, the design will undergo technical review by the Center project or engineering office. It will also be reviewed by Center engineers not directly associated with the project, engineers from other NASA Centers, and/or other specially qualified consultants.

In the case of the 40X80 wind tunnel repair project, there is a center review committee and a NASA oversight panel which review major technical decisions and overall project management. The procedure is not unique to this project. These forums, in which recognized experts in various disciplines participate, reduce the risk of a faulty design approach. A similar center review committee and/or NASA oversight panel will be instituted as needed for all major facility projects that involve new or complex technology.

oo CONFIGURATION AND CHANGE CONTROL PROCEDURES

The framework for proper change order and documentation control procedures is provided for in Center management instructions, project management plans, and the NASA "Facility Project Implementation Handbook." The handbook requires a management plan for all large or technically complex construction projects. These management plans are reviewed and approved at both Center management and the Headquarters level. All management plans follow a similar format, and instructions have been issued for their content. Over the past year renewed emphasis has been placed on developing, revising, and refining these plans so that they are not only essential but also very useful in designing and constructing facility projects. Being specific to a particular project, they have the flexibility necessary for the peculiarities of the project and the management techniques of the individual project management staff.

Change order control procedures are a part of NASA's facility project instructions and each facility management plan. These procedures have, in the past, addressed change orders primarily from the standpoint of cost and schedule impact. It is once again clear that safety must also be an important consideration in the change order review, approval, and implementation system. Although a safety review has normally been part of the change order system, procedures are being rewritten in the facilities handbook to insure greater emphasis on the safety review. Project management plans now require center and, in some cases, Headquarters management participation in the change order process.

A part of the change control system is documentation control. At some NASA Centers existing written procedures do not adequately address the need to keep contract documents and drawings up to date. Action is underway to correct this deficiency in our facilities handbook.

There is also a renewed emphasis on an adequate level of quality inspection of construction. In the past, contracts have occasionally required self-inspection by the contractor, with limited Government inspection. It has been found that contractor self-inspection does not provide the expected or desired quality of construction.

It is recognized that institution or emphasis of some of these procedures may result in increased costs to the projects. This "insurance premium," however, can result in lessening the risk of a major facility related accident.

oo NASA FACILITIES PROJECT IMPLEMENTATION PROCEDURES

In March 1981 a NASA Facility Project Implementation Handbook (NHB 8820.2) was published[2]. This handbook provides instructions for a systematic approach to facility planning, design, and construction, and consolidates all the various NASA design and construction letters of instruction previously issued. The handbook was reviewed in early 1983 by each NASA Center facilities division and by the Headquarters facilities office. Additionally, the handbook was reviewed in the fall of 1983 by a consultant specializing in project management. The consensus was that the handbook is an adequate management tool. However, several areas have been earmarked for clarification, update, or emphasis. We are currently conducting a final review of the handbook update to insure that it will include, with the proper degree of emphasis, all the appropriate revisions. It is expected that the changes to the handbook will be drafted by the early months of 1984.

oo OBSERVATION ON ORGANIZATION

A NASA Headquarters reorganization occurred late in 1981 which changed some responsibilities for NASA's facilities programs. However, there were no indications that this change played a role in the Ames accident. The reorganization revised the procedures for identifying and developing facility project requirements and concepts. Each Headquarters program organization (Space Science and

Applications, Space Flight, Space Tracking and Data Systems, Aeronautics and Space Technology) is responsible for the development, prioritization, and coordination of their facility requirements. The program offices are in turn provided technical facilities engineering support by the Facilities Engineering Division. The Facilities Engineering Division continues to translate the program office requirements into budgeted facilities projects. This recent definition of the requirements role of the program offices and the implementation (design/construction) role of the Facilities Engineering Division has improved the timely preparation and advocacy of the C of F Budget. The Facilities Engineering Division continues to approve, implement, and manage all approved CoF projects at the Headquarters level.

CONCLUSIONS

A comprehensive review of NASA's design and construction procedures has shown that the prescribed procedures are adequate when carefully followed. Some revisions and re-emphasis of the procedures are underway to make maximum benefit of the lessons learned from the 40X80 wind tunnel accident. It is recognized that highly technical and complex projects require exceptionally stringent management controls, and that adherence to those controls is mandatory. The 40X80 wind tunnel lessons have been strongly emphasized to all levels and locations of NASA's facility engineering and management staff. With a re-emphasis on proper design review, control of changes, and safety, the likelihood of a future major construction related accident should be a greatly reduced.

Appendix 1: 40X80 Wind Tunnel Accident Investigation Board Recommendations

References:

1. "Report of 80- by 120-Foot Wind Tunnel Accident Investigation Board to Administrator, National Aeronautics and Space Administration," March 2, 1983.

2. "NASA Facility Project Implementation Handbook (NHB 8820.2)" March 1981.

APPENDIX 1

40X80 WIND TUNNEL ACCIDENT INVESTIGATION BOARD RECOMMENDATIONS

The Accident Investigation Board made 17 recommendations concerning management of construction and operations of the Ames Research Center 40X80 Wind Tunnel. The recommendations are directly transferable to construction and operation of any high technology, high cost, or high risk project. The recommendations fall into three general categories; design and construction, design documentation and change order controls, and operations safety. Wind tunnel operations are outside the scope of this report.

oo DESIGN AND CONSTRUCTION RECOMMENDATIONS

RECOMMENDATION 1:

"An in-depth evaluation of damage to 40x80x120-Foot Tunnel system other than Vane Set No.5 and the fan drive is required before the re-built facility is returned to service."

This evaluation is complete. Considerable latent damage was uncovered during the evaluation and is being corrected.

RECOMMENDATION 2:

"A detailed review/evaluation of the design, expected loading, and construction inspection for all tunnel components should be performed prior to resuming operations with the rebuilt tunnel."

This review and evaluation has been accomplished and has uncovered requirements for structural modifications to additional vane sets.

RECOMMENDATION 3:

"Designs for unique facilities such as the 40x80x120, which do not admit of empirical development, should utilize concepts which maximize load predictability and structural reliability."

This recommendation is to encourage use of all available tools for design development, including structural analysis, model aerodynamic testing, mathematical modeling, etc.

RECOMMENDATION 4:

"The use of higher than normal safety factors is encouraged in the design of unusual structures exposed to high energy air streams where failure will result in injury, significant cost, or lost time."

The judicious use of conservative safety factors is common practice in construction design, but must also be balanced against economic considerations.

RECOMMENDATION 5:

"When the parameters that control the design of a facility cannot be obtained from the literature or developed by analysis, realistic model testing of the configuration chosen should be performed prior to final design, and sufficient structural margin should be incorporated in the design to provide for all residual uncertainties in the loads."

The 40x80-foot wind tunnel project did receive some (but not complete) aerodynamic model testing. The policy in the tunnel repair project is to aerodynamically test and analyze models of each new component concept before it is included in the final decision.

RECOMMENDATION 6:

"An independent third party design review should be performed on in-house design in the same fashion as would apply for A&E designs."

Much improved procedures now insure that all designs are reviewed by people other than the designers. For example, Ames and NASA oversight panels have been established to review and approve all major design decisions for the 40X80 wind tunnel repairs.

RECOMMENDATION 7:

"A vigorous construction quality assurance program should be established at the Center to provide surveillance of construction quality and to assure that the as-built configuration conforms to the approved drawings or to the approved deviations. This function, in addition to the responsibility for inspection, should provide an expertise/repository of knowledge in non-destructive evaluation (NDE) techniques and should be staffed to a significant degree by in-house personnel. Such a construction quality assurance unit should be a 'line organization' responsibility rather than a project responsibility to provide continuity of expertise."

The repair work on the 40X80 tunnel and future project work will have much stronger inspection procedures with an adequately manned inspection staff. Past procedures using some contractor self-inspection have proven to be only marginally effective.

RECOMMENDATION 8:

"All high energy facilities and systems should be subjected to a single failure point/failure modes and effects analysis (SFP/FMEA) prior to their initial operation. All SFP's that could cause Category I (catastrophic) failures should be acceptable only if accepted by the Center Director."

Safety analyses play a major role in the design of the repair project. Facilities design instructions are being modified to mandate more complete and stringent analyses than previously required.

oo DESIGN DOCUMENTATION AND CHANGE ORDER CONTROL RECOMMENDATIONS

RECOMMENDATION 1:

"All changes to the configuration of the Wind Tunnel should be accomplished only after a Request for Change (RFC) has been prepared and approved by a project configuration and change control board. The board should utilize a face-to-face procedure so that pros and cons and opportunities or options can be fully discussed."

The current change order procedure is very thorough and specific and should preclude any change to the project design, schedule, or cost without full documentation and approval by the change control board or higher reviewing authority.

RECOMMENDATION 2:

"All drawing originals/masters should be retained and controlled through the Engineering Information Center (EIC) following release from engineering for either fabrication or contracting purposes. All changes to master drawings would be performed by the EIC following an approved request for change or engineering change order."

A special group now exists for document control. No construction change to the approved design is permitted until entered on the master design sheets by this group, and new design sheets distributed by this group to all concerned parties. This group is an integral part of the change control procedure, discussed above.

RECOMMENDATION 3:

"All hardware modifications to facility structures/components which affect form/fit/function should be performed only with documented procedures made available to contractors and tunnel mechanics. Likewise, all adjustments to or re-positioning of major tunnel components which result in altered loads to the facility structure/components should be performed only using approved documented procedures."

This recommendation is applicable to both the construction and operational phases of the project. During construction, modifications will come under the purview of the Change Control Board and Engineering Information Center. Procedures are being developed for proper documentation of modifications during tunnel operations.

oo OPERATIONS SAFETY

(Although separate comment for each of the following operations recommendations is not made, every recommendation is being incorporated into the tunnel activation planning and subsequent test operations.)

RECOMMENDATION 1:

"A formal system for establishing and communicating the maximum allowable condition, i.e., red lines, should be established for all critical parameters prior to resuming the operation of the rebuilt tunnel."

RECOMMENDATION 2:

"Sufficient diagnostic instrumentation (strains, dynamics, pressures, flow direction, temperature, etc.) of suitable accuracy and frequency responses should be incorporated into shakedown testing of the rebuilt tunnel to permit a good assessment of facility/component loads, flow quality, and readiness for research operations."

RECOMMENDATION 3:

"Measurements on components which could cause catastrophic failure should be continously monitored or interlocked into the operation so that 'red line' violations would terminate the test."

RECOMMENDATION 4:

"When gross deviations from expected data values are found during commissioning tests, the test should be interrupted and a detailed analysis of all systems associated with or affected by the deviation should be performed prior to further operation."

RECOMMENDATION 5:

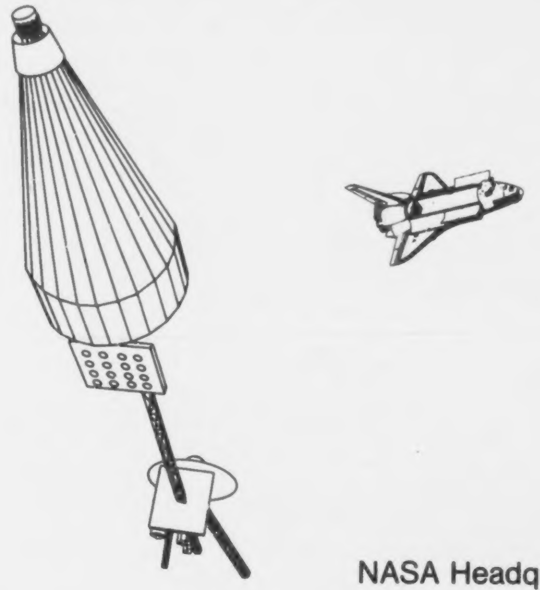
"Observation of structures or models with some probability of disintegration should be made with closed-circuit television or other means of remote monitoring if there is a possibility that the debris might endanger a human observer."

RECOMMENDATION 6:

"A facility log should be kept to record all work and maintenance activity performed on facility structure and components. Such a log would establish a documented history of such activities useful for future reference in facility modification/maintenance."

National
Aeronautics and
Space
Administration

Civil Applications Of Nuclear Power - Final Report Of The Civil Missions Advisory Group



NASA Headquarters
September 1984

CIVIL APPLICATIONS OF SPACE NUCLEAR POWER -

FINAL REPORT OF THE CIVIL MISSIONS ADVISORY GROUP

NASA HEADQUARTERS

AUGUST 1984

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1. EXECUTIVE SUMMARY

The Civil Missions Advisory Group (CMAG) was established by NASA in the third quarter of 1983 to address concerns expressed by the Committee on Science and Technology in House Authorization Report 98-65. These concerns relate to the interface between civil and military use of space reactor power systems and the timing of future applications. At present, the assessment of space reactor technology and mission applications is being conducted in the SP-100 program. This program is managed under a Tri-Agency Agreement among NASA, DOE, and DARPA.

To assure the House Committee that civil mission needs are being adequately analyzed and defined, NASA formed and directed CMAG to carry out the following responsibilities: 1) review the mission planning and definition activities associated with the SP-100 program and other areas within NASA that involve potential use of space nuclear power; 2) advise the NASA Administrator and the Tri-Agency Steering Committee on all significant civil missions; 3) recommend additional studies as needed; and (4) advise the Administrator and Congress on NASA's role in the transition of this technology to flight readiness.

More than 50 candidate missions were brought to the attention of CMAG through review of NASA in-house and contractor studies, advisory committee recommendations, and recent work within the SP-100 Program. The following criteria were broadly applied to the selection process relevant to the issue of space nuclear reactor application: 1) is the electrical power requirement above some minimum entry level; e.g. 50 kW?, 2) does nuclear power enhance mission performance or its practical implementation?; 3) are the mission objectives supported by established goals for space exploration/application and a clearly identified user community?; and 4) is the mission likely to be implemented in the foreseeable future (1990-2020) on the basis of technology readiness and cost acceptability?

The civil mission set determined to be realistic for planning purposes is comprised of more than 10 representative missions in several application classes as shown in Table 1-1. The first of these is a manned facility in low Earth orbit as typified by the initial space station soon to be

Table 1-1

CIVIL MISSION SET - CHARACTERISTICS MATRIX

MISSION	POWER UTILIZATION FUNCTION	REGION OF OPERATION	POWER LEVEL (KW)	MISSION TIME (YRS)	NUCLEAR POWER BENEFIT	MISSION EPOCH
MANNED ORBITAL FACILITY						
INITIAL SPACE STATION	MULTIFUNCTION	LEO	75-150	10	ENHANCING	1990-2000
GROWTH SPACE STATION	MULTIFUNCTION	LEO	300-500	10	SIGNIFICANT	2000-2010
ADVANCED SPACE STATION	MAT. PROCESS	LEO	500-1000	10	SIGNIFICANT	2000-2010
EARTH SCIENCE AND APPLICATIONS						
GEO COMMUNICATIONS PLATFORM	COMMUNICATIONS	GEO	100-200	10	SIGNIFICANT	1990-2000
AIR/OCEAN TRAFFIC CONTROL	OBS. - EARTH	LEO	100-200	10	SIGNIFICANT	2000-2010
TRANSPORTATION						
GEO PAYLOAD DELIVERY	TRANSPORT (EP)	LEO-GEO	100-200	5*	ENHANCING	1990-2000
LUNAR PAYLOAD DELIVERY	TRANSPORT (EP)	LEO-LUNAR	100-200	5*	ENHANCING	2000-2010
MANNED MARS MISSION	TRANSPORT (EP)	IP SPACE	ABOVE 1000	3	SIGNIFICANT	BEYOND 2010
EXTRATERRESTRIAL RESOURCES						
LUNAR BASE RESOURCES	MAT. PROCESS	LUNAR	200-500	10	SIGNIFICANT	2000-2010
ASTEROID BASE RESOURCES	MAT. PROCESS	N.E. SPACE	200-500	5	SIGNIFICANT	BEYOND 2010
PLANETARY EXPLORATION						
MULTI-ASTEROID SAMPLE RETURN	TRANSPORT (EP)	IP SPACE	100-200	8	SIGNIFICANT	2000-2010
COMET NUCLEUS SAMPLE RETURN	TRANSPORT (EP)	IP SPACE	100-200	6	ENHANCING	1990-2000
SATURN RING RENDEZVOUS/EXPLR	TRANSPORT (EP)	IP SPACE	100-200	10	SIGNIFICANT	2000-2010
FAR OUTER PLANETS ORB/PRB	TRANSPORT (EP)	IP SPACE	100-200	10	SIGNIFICANT	1990-2000

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* MULTIPLE SORTIES

developed, and later by growth versions which may have more specialized functions such as high-production materials processing and manufacturing. Another class of missions having direct utility to Earthbound society includes advanced, multi-function communications platforms in geosynchronous orbit and powerful radar platforms for traffic control of commercial air and sea routes. The third applications class is transport of large payloads to geosynchronous orbit and the Moon, using electrically propelled space tugs in the case of the nuclear power option. Moving away from Earth, materials processing bases may be established on the Moon and on nearby asteroids to take advantage of the potential resources residing on these bodies. Scientific exploration of the solar system, particularly orbiter/probes of the outer planet systems and sample return from comets and asteroids, would benefit significantly from high power to drive electric propulsion systems.

Civil mission energy requirements are characterized by long-term operations (3-10 years) and nearly continuous power demand. The functional use and amount of power required varies widely across the mission set. Dominant usage categories are materials processing, electric propulsion, and communications/radar transmission. Electrical power requirements generally range from 50 to 1000 kW; a considerable number of missions would function well at the 100-200 kW level.

All of the civil missions identified in this selection are enhanced to some degree by the availability of a nuclear reactor power source. In several cases the performance enhancement is very significant and possibly enabling. This assessment allows for the fact that alternative power systems (primarily solar photovoltaic and solar dynamic) or other means of mission implementation (e.g. chemical propulsion) are also available and could be employed for a number of these missions.

Results of the first phase of the CMAG study, summarized above, were documented in an Interim Report published in March 1984. To complete the CMAG's FY'84 activities, it was decided to focus attention on three mission areas considered to be high-priority candidates for utilization of space nuclear power. These are: space station; advanced communications and radar observations; and planetary exploration. This final report contains in-depth discussion of these areas in terms of mission rationale, objectives and performance requirements related to high power need. Other key issues addressed here are comparisons with alternative power systems, specific benefits and liens of nuclear power use, and safety assurance in the development and operation of reactor systems.

A nuclear power system is an excellent candidate for the growth space station where power requirements are perceived to exceed 300 kWe. The two most viable design configurations are a boom-mounted reactor with electrical transmission of power, and a tethered reactor with power generated at the station using regenerative fuel cells fed by hydrogen/oxygen fluids transmitted over tether hoses. Of these two designs, the boom-mounted system requires the lowest initial mass and volume in orbit and the fewest number of Shuttle flights. The reactor is located 70 meters from the station and is well-shielded to provide safe radiation levels for manned operations in the station (5.7 mrem/hr) and limited EVA operations near the reactor (200 mrem/hr). The man-rated shield represents a very substantial fraction of the total power system mass of 31,000 kg. In this configuration, the station attitude is controlled in the highly stable gravity-gradient mode. A major recommendation of the study is that the initial space station design effort should account for efficient changeout from solar to nuclear generated power at some future date.

A multi-function communications platform in geosynchronous orbit requires more than 100 kWe of primary power for sustained operations. Typical functions include direct broadcast video, advanced video teleconferencing, electronic mail transmission, and mobile communications. Nuclear power enhances the viability of such a platform by providing lower cost power not only for signal transmission, but also for electric propulsion utilization in stationkeeping maneuvers. The nuclear power source is unaffected by solar direction and Earth eclipse periods, thus permitting simpler attitude control/antenna pointing and optimal longitudinal location of the platform. The second type of mission in this service category is commercial air traffic control provided by space-based radar systems. The capability of near-continuous, accurate tracking (75 meters vertically, 500 meters horizontally) could reduce aircraft spacing by 75% or more with greatly reduced risk of mid-air collisions, thus permitting reduced departure and arrival delays, timely changes in flight plan due to weather, and greater fuel efficiency. Radar power requirements are in the range 50 to 200 kWe depending on such factors as tracking resolution, orbit altitude, number of targets, range of coverage, and antenna size. Several radar platforms in mid-altitude orbits represent the best engineering solution. Nuclear power offers significant benefits related to duty cycle independence of the Sun, attitude control, and operation in the Van Allen radiation regions without power degradation.

The benefits to planetary exploration derive from use of electric propulsion systems powered by a nuclear reactor for delivery of the spacecraft science experiments and subsystems needed to carry out advanced exploration objectives. Specific missions such as Asteroid and Comet Sample Return, Saturn Ring Rendezvous, and Far Outer Planets Orbiter/Probes have been identified, but other applications exist as well. Nuclear-electric systems in the power range 100 to 200 kWe generally provide greater payload mass and significantly shorter flight times than alternate means of payload delivery such as chemical propulsion and solar electric propulsion. The Saturn Ring Rendezvous mission can be performed only by nuclear electric propulsion.

At the present time, it is sufficient to identify a broad range of civil missions having high power requirements, to describe the most important applications, and to show that significant benefits accrue with the development of space reactor power systems. CMAG believes it has accomplished this task by its process of review and assessment. Narrowing the group of missions to a specific one only becomes necessary at the time of commitment to flight power system development. This can be reasonably expected to take place in the late 1980's as critical technology issues are resolved and particular missions are assessed to the degree necessary to permit implementation. As a near-term example of this plan, Table 1-2 presents the direction being taken in mission analysis and requirements activities through FY'85.

Table 1-2

MISSION ANALYSIS & REQUIREMENTS ROADMAP

ELEMENT	JULY 1984	JULY 1985
• Mission Commitment	Statements made showing interest in missions requiring SNP*	Written statement that SP-100 will most likely be required - MENS** & NASA equivalents available
• Mission Funding & Sources	Mission Agencies not funding SP-100; SP-100 Project conducting general mission studies	Mission Agencies are studying nuclear options
• Mission Definition	Missions defined in generic classes only	A candidate mission from each category is characterized well enough for trade-off charts (Mission Performance vs. Power System Performance)
• Mission Payloads and System Definition	Modelling for mission characterizations allow some mission performance vs. power system parameters	Spacecraft concept investigations validate need for SNP
• Required Mission Related Documentation	Mission Requirements Report	Design Goals & Requirement Document

* SNP = Space nuclear power
** MENS = Mission element need statement

Surety* of flight and ground test systems is universally considered critical to the success of the space nuclear power development program. Accordingly, surety is given the highest priority in the SP-100 Program to ensure that minimum, acceptable risk is presented to the general population, the environment, mission personnel, facilities, and equipment. A Surety Program Plan is being finalized which will cover all safety aspects of space nuclear power system technology from conceptual design and development through testing and deployment to ultimate disposal. A Safety Advisory Committee has been established to advise the project on matters of safety and safeguards and other aspects of the project which may relate to safety. Safety issues, analyses, and tests will be identified and the impact of safety on all elements of the program will be clearly defined in the Surety Program Plan.

The SP-100 Surety Program will provide confidence that safety will be adequately integrated into the design and that flight approval can ultimately be obtained while minimizing undue design penalty implications. To achieve this objective during the Technology Assessment and Advancement Phase, the Surety Program will focus on establishing preliminary safety criteria with supporting technical bases. These preliminary criteria will be approved by the SP-100 Program Office and reviewed by appropriate independent bodies to ensure that there is a broad consensus by July 1985. In addition, for each phase of the SP-100 Development Program, the Surety Program will establish, or actually demonstrate, the feasibility of compliance in meeting the safety, safeguards, and environmental protection criteria by producing a technical base of analysis and test results, reviewing contractor results, and performing independent analysis and testing where required. Where feasibility cannot be demonstrated by July 1985, open issues and potential resolution paths will be identified for resolution in phase II of the Development Program.

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* Surety is an integration of safety, safeguards, environmental protection, reliability, and quality assurance.

2. INTRODUCTION AND BACKGROUND

Space power needs, primarily in the form of electrical power, have been relatively modest during the first twenty-five years of the Space Age. These needs have been satisfied by well-understood and developed technologies such as photovoltaic (solar) cells with battery storage, chemical fuel cells, and radioisotope thermoelectric generators. The next generation of space missions will require the development and use of power systems having higher efficiency, lower specific weight, longer lifetime, greater reliability, and lower cost.

It is reasonable to project an accelerating growth in space activities during the next few decades brought about by real and perceived mission need in combination with available new technology. Much of this activity will require large amounts of power, 50 to 1000 kWe, either to implement the primary mission goals or to satisfy the means of payload delivery. A variety of mission applications has been conceived and is being planned in such areas as space sciences and planetary exploration, Earth observation and communications, manned orbital stations, and commercial ventures in space manufacturing and resource utilization.

Space power systems development will likely follow two concurrent paths depending on the application requirements and time period of interest. One path will focus on the evolutionary development of current approaches such as improved solar cells, concentrating-array elements, and more efficient energy storage devices. The second path will involve new developments in advanced, mission-enabling technologies such as solar-dynamic and nuclear reactor power systems.

Studies of competing energy sources suggest that nuclear reactor systems have the potential of being more mass-efficient and more economical than solar array systems for high power applications. These primary benefits are complemented by other advantages in the operational environment of a power system and its host space vehicle. A space reactor system is inherently independent of the Sun and thus can operate on a full duty cycle without needing large energy storage devices during eclipse or local night conditions. Solar independence also implies a simplified attitude control requirements which may allow improved accuracy for instrument pointing and target tracking. Nuclear systems have a much smaller cross section area than solar array power sources. This attribute results in several important benefits: 1) reduction in drag-makeup propellant required to maintain altitude in low Earth orbit applications, 2) lower risk of damage due to meteroid or space debris impacts, 3) better field-of-view for pointed experiments, and 4) less interference for large structures assembly operations. Another benefit to be noted is that the inherent "hardness" of a nuclear system enhances survival in contaminating environments and, in particular, allows operation in natural radiation fields (e.g. Van Allen Belts) without suffering degradation of power output.

A growing awareness of high-power mission applications, both civilian and military, led to the formation of the tri-agency SP-100 program in 1983. This program is defined in an agreement among NASA, DOE and DARPA to carry out a comprehensive assessment of space nuclear reactor technology leading to a possible decision to undertake engineering development. Objectives of the SP-100 activity are to obtain a better definition of mission applications and requirements, to evaluate alternative system designs, to assess and develop the required technology, to ensure that safety is fully considered, and to plan a subsequent phase of engineering development. The first phase of this program extends through FY 1985 and will provide the technical basis for deciding whether or not to proceed further.

The Civil Missions Advisory Group (CMAG) was established by NASA in the third quarter of 1983 to address concerns expressed by the Committee on Science and Technology in House Authorization Report 98-65. These concerns relate to the interface between civil and military use of space reactor power systems, and the timing of future applications. Qualified representatives from Headquarters and NASA field centers were selected for this assessment task. The membership of CMAG is listed on the opening page of this report.

The objectives and responsibilities of CMAG are as follows:

1. Review the planning and mission definition activities associated with the SP-100 program.
2. Advise the NASA Administrator and the Steering Committee of SP-100 on all significant civil missions.
3. Recommend additional studies, as needed, of non-military applications of nuclear reactor power technology.
4. Advise the Administrator and Congress on NASA's role in the transition from technology development to flight operations.

CMAG has carried out these responsibilities through its directed requests for technical information, deliberations at working group meetings, and preparation of report materials. An Interim Report describing the selected set of civil missions and their requirements was published in March 1984 (Ref. 2-1). That document together with this final report represents the CMAG's FY'84 activities.

The purpose of this report is to provide a greater depth of information concerning three civil mission applications areas of significant interest and potential for early utilization of space nuclear power. These areas are: 1) growth space station; 2) advanced communications and observation systems for public service utility; and 3) scientific exploration of the solar system. In addition to descriptions of mission rationale, objectives, and requirements, each of these sections of the report will address the design implications of operating in a nuclear radiation environment and possible alternatives to nuclear power systems. The report also discusses one of the most important issues related to the use of nuclear power, namely, safety assurance in all phases of development and flight operations.

3. SPACE STATION

3.1 Introduction

Of all of the five sets of civil missions applicable to nuclear power, the manned Space Station is the one of most immediate interest in view of the Administration, and now Congress, opting to proceed with the Space Station. This discussion will describe the trend in manned Space Station missions leading to a recommendation for nuclear power on the Growth Station. Included are identification of several nuclear-powered Station concepts, and a comparison with alternative power systems.

One of the major investigations undertaken by the SP-100 program was to determine power requirements in the area of identifying applicable nuclear missions. To this end a separate study contract, among others, was awarded to the Boeing Company through NASA LeRC to investigate the applicability of 100 kWe class space reactor power systems to NASA manned Space Station missions (Ref. 3-1). A condensation of the contracted and in-house studies is included herein.

The nuclear-powered Space Station study had four tasks:

1. To identify manned missions that would materially benefit and/or be enabled through the use of nuclear power, and their respective power requirements.
2. To assess the impact of the presence of a nuclear electric power system (NEPS) on the architecture of the Space Station with particular emphasis on safety.
3. To prepare three conceptual designs of a NEPS, including on-board, tether, and free-flyer approaches.
4. To document the study in a final report.

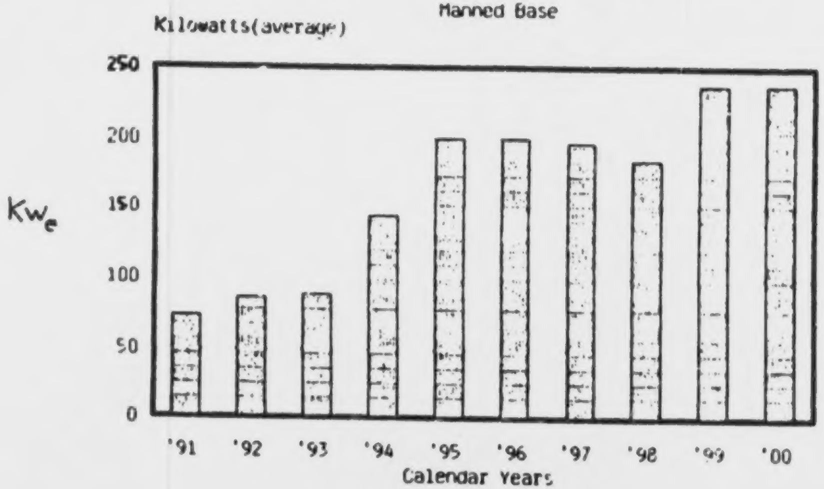
Space Station Mission Requirements

It was found in Task 1 that Space Station missions that may benefit from the use of a nuclear reactor power source are the power-intensive materials processing missions and those that require broad accessibility over large volumes near the station. The Space Station Mission Requirements Working Group (MRWG) maintains a current data base of Space Station

Figure 3-1

Average Power Requirements for Space Station Payloads

28.5°, Station Mission Power



AVERAGE POWER REQUIRED FOR PAYLOADS ON MANNED SPACE STATION

DOES NOT INCLUDE HOUSEKEEPING POWER

FROM NASA SPACE STATION MISSION REQUIREMENTS REPORT MAY 8, 1984

mission requirements for planning purposes. The most recently compiled summary, Figure 3-1, projects an average power requirement of 200 to 250 kWe for missions in the mid to late 1990's (in process of being revised). Peaking needs and space station housekeeping will likely raise this need to over 300 KWe to perform the missions in the MRWG data set. Additional missions made feasible by the availability of sufficient space station power, or by a robust commercial materials processing industry, might lead to a requirement for 300-400 kWe by the late 1990's. At these high power ranges it is perceived that system designs employing very large solar arrays become difficult to construct, maintain and control. The NEPS would simplify station dynamics, eliminate precise continual orientation requirements, enable ready access to the Station by the Shuttle and for Extra Vehicular Activity (EVA), and has very low atmospheric drag. Also, its compactness facilitates the assembly of large space structures such as antennae, and provides almost unimpeded viewing for on-board experiments and operations.

Reference Space Station Mission Set

NASA's Space Station Task Force has compiled and keeps current a reference file of Space Station mission descriptions (Ref. 3-2). This reference file was originally established as a validated summary of missions identified by the eight NASA contractors of the Space Station Needs, Attributes, and Architectural Options Study during fiscal year 1983. The Mission Requirements Working Group reviewed all the contractor mission descriptions in May, 1983 to establish a single planning document. This document represents NASA's mission set for Space Station definition and preliminary engineering activities.

The complete set of missions considered by the MRWG includes candidate missions in three categories: Science and Applications, Commercial Utilization, and Technology Development. These categories are each summarized by a discipline panel which interfaces with its respective user community to analyze and assemble potential missions which could be supported by a space station system. Data included in the Space Station Mission Requirements data base are brief mission descriptions; time phasing and requirements of resources such as power, data transmission rate, crew time, volume, and mass.

The complete space station system includes more than just a single, manned facility. It includes a manned facility, free-flying platforms in various orbits, service vehicles, orbital maneuvering vehicles, and the launch and resupply vehicles of the Space Transportation System. The current reference mission set for the 1990's considers a single Space Station in low-inclination, 28.5° low-earth orbit as its only permanently manned facility. Other facilities that may occasionally be visited by man include platforms in low altitude polar orbit and in geosynchronous orbit.

About eighty percent of the power required that is identified in the MRWG mission sets is that needed for materials processing missions. The greatest power demand comes from various crystal growth production units, biological processing production units, optical fiber production, and the Materials Processing Science (MPS) laboratory. Some of these missions and their load characteristics are described below.

3.2 Materials Processing Mission Descriptions

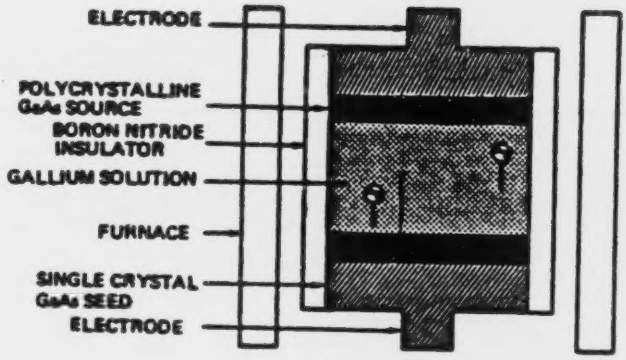
Crystal Growth

Electroepitaxial (ECG)

Semiconductor crystal growth missions include electroepitaxial crystal growth (ECG), chemical vapor transport growth (VCG), and directional solidification (DSCG). Electroepitaxial crystal growth of gallium arsenide is illustrated in Figure 3-2. A saturated solution of a few percent gallium arsenide in gallium is brought into contact with a monocrystalline seed crystal and a polycrystalline source crystal. When electric current is established normal to the seed-solution interface, the arsenic ions migrate toward the seed crystal and crystallize with the solvent on the surface of the seed. As long as the solution remains saturated near the growth region, highly stoichiometric and uniform crystallization occurs by epitaxial growth. The electric current forces transport of the solute to the seed crystal interface so that this region remains saturated as uni-

Figure 3-2

ELECTROEPITAXIAL CRYSTAL GROWTH


ELECTRODE
POLYCRYSTALLINE GaAs SOURCE
BORON NITRIDE INSULATOR
GALLIUM SOLUTION
FURNACE
SINGLE CRYSTAL GaAs SEED
ELECTRODE

- ISOTHERMAL (800–850°C)
- ELECTRIC CURRENT DRIVES As to seed (J = 10–50 A/cm²)
- SOLUTION REPLENISHED BY SOURCE
- ZERO G ELIMINATES BUOYANT CONVECTION CAUSED BY OHMIC HEATING

form single crystals are grown. The solute concentration is maintained by dissolution, diffusion, and current-driven transport from a polycrystalline source. The process is carried out inside a furnace which maintains precise control of the crystal growth temperature. The temperature range being considered is 800-950° C.

The electric current densities required for current-controlled electroepitaxial growth are in excess of 10 A/cm^2. This current flows through the melt and the crystal. Resistive heating and Peltier cooling at the interface cause temperature gradients in the melt. In a gravitational field these temperature gradients would cause thermal convection, which would destroy the uniformity of the crystal. Thermal convection does not occur under microgravity conditions. Therefore high current densities are allowed in the microgravity environment of space and, since growth rate is linearly proportional to current density, rapid growth of large, uniform, compound semiconductor crystals is provided.

Microgravity Research Associates, Inc. is developing the electroepitaxial growth process for space-based growth of gallium arsenide (GaAs) crystals. GaAs is superior to silicon as a semiconductor in several respects. It has a much faster switching speed, lower power requirements, lower heat loss, and higher temperature resistance. All of these important attributes of GaAs fortuitously combine to readily permit the use of higher current element densities with greatly enhanced processing speeds and reduced cooling requirements. Furthermore, GaAs is much more resistant to radiation than is silicon, allowing its use in nuclear, space, and military environments where silicon-based semiconductors degrade.

Ground-based GaAs growth experiments have been performed with low current densities and small dimensions to suppress thermal convection, but low-g experimental verification of the concept must await spaceflight. Microgravity Research Associates has a Joint Endeavor Agreement with NASA to develop the electroepitaxial growth process for gallium arsenide.

The electrical power required for electroepitaxial growth of gallium arsenide depends on both temperature and thickness of the crystal. At

875° C furnace temperature, the energy required to grow 1 cm thick GaAs crystals in five days is about 66 kWh/kg. In addition to the energy required for the growth current, an additional energy of 40 kWh/kg is required to maintain the furnace temperature for five days.

The estimated market demand for space-produced gallium arsenide is shown in Figure 3-3. The projections assumed market prices that reflect decreasing production costs resulting from the following flight scenario: in 1990, crystals are grown in the orbiter on six day missions; in 1991, crystals are grown on a free-flying platform which is serviced by the orbiter; in 1992-93, crystals are grown in dedicated modules attached to the space station; beyond 1993, crystals are grown in free-flying platforms serviced from the space station. The average power required to satisfy these demand projections is shown in Figure 3-4. In the mid-1990's, the power required for electroepitaxial growth of gallium arsenide is likely to be in the range of 10-30 kW. By the year 2000, this value is expected to rise to as high as 100 kW. In the MRWG reference set, a ground rule for the Station's Initial Operational Capability (IOC) has been observed which limits the space station-supplied power for any single commercial mission to 20 kWe. This power limitation has been lifted for later years and has resulted in greatly increasing the forecasts for power requirements beyond IOC.

Chemical Vapor Transport

Another method which is currently used for growing semiconductor crystals involves transport of the crystalline elements from a source to a growth crystal in the vapor phase, as depicted in Figure 3-5. To grow crystals with this chemical vapor transport method, a polycrystalline source of material is heated in the presence of a gaseous transport agent. A chemical reaction between the source and the transport agent results in exclusively gaseous products which are removed from the source. The growth crystal is located at the other end of the growth ampoule, and is maintained at a lower temperature than the source material. The gaseous products are transported down the temperature gradient to the growth crystal, where they undergo the reverse chemical process and condense into the orginal chemical product, in pure monocrystalline form.

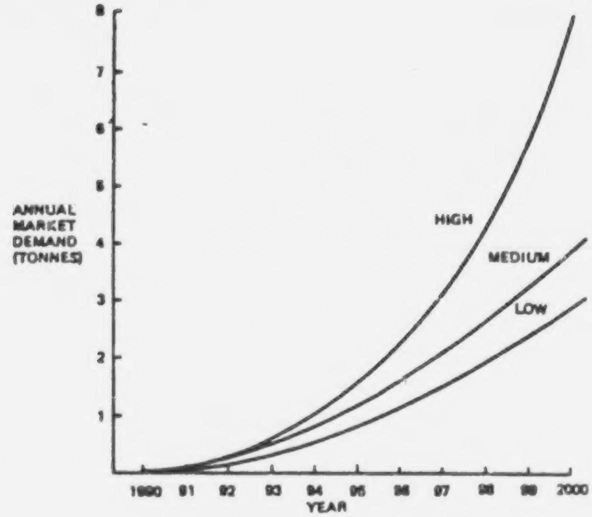


Figure 3-3 SPACE-PRODUCED GALLIUM ARSENIDE MARKET PROJECTIONS

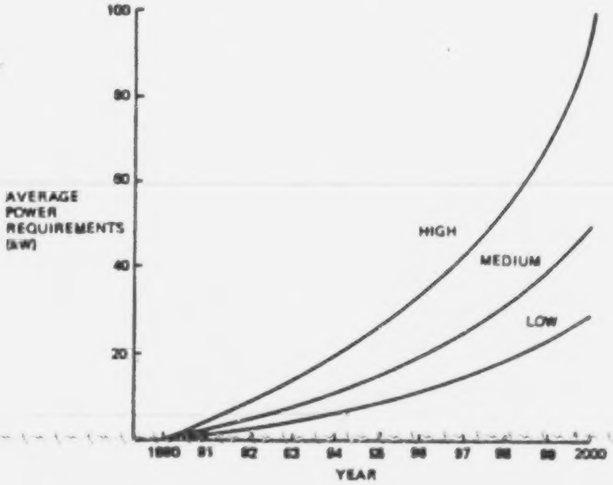


Figure 3-4 AVERAGE POWER REQUIRED FOR GALLIUM ARSENIDE PRODUCTION

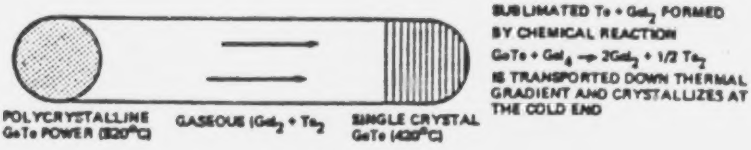

SUBLIMATED Te + GeI$_2$ FORMED BY CHEMICAL REACTION
GeTe + GeI$_4$ → 2GeI$_2$ + 1/2 Te$_2$
IS TRANSPORTED DOWN THERMAL GRADIENT AND CRYSTALLIZES AT THE COLD END
POLYCRYSTALLINE GeTe POWER (520°C)
GASEOUS (GeI$_2$ + Te$_2$
SINGLE CRYSTAL GeTe (420°C)

Figure 3-5 CHEMICAL VAPOR TRANSPORT EPITAXIAL CRYSTAL GROWTH

The crystal uniformity of the product reflects the uniformity of the vapor phase. In full gravitational fields, thermal convection of the vapor disturbs the uniform flow and limits the crystal perfection. Thermal convection does not occur to a significant degree in microgravity, so more uniform crystals can be made at high growth rates.

This process is being developed at Rensselaer Polytechnic Institute for growth of large, monocrystalline, compound semiconductors. Previous experiments have been performed with germanium and group VI compounds. Future plans call for vapor phase growth of large, ternary semiconducting compounds, such as $Hg_xCd_{1-x}Te$. These could be used as infrared detectors, with a response function which can be selected by choosing the value of x.

A series of crystal vapor growth experiments is scheduled on the Materials Experiment Assembly-A facility aboard the Orbiter. The first flight was on STS-6. The crystal material on this flight was germanium-selenium. On all subsequent flights, beginning in August 1984, it is planned to produce mercury-cadmium-telluride crystals with the facility.

Directional Solidification (DSCG)

Directional solidification crystal growth techniques can be applied to semiconductors of metals. In general, the material to be crystallized is melted in a crucible within a furnace. The furnace is designed with a temperature profile which encompasses temperatures above and below the melting point. Crystal growth occurs at the cooler end of the crucible. The crucible is either stationary or it is slowly pulled out of the furnace, down the thermal gradient. In either configuration, crystal growth proceeds as a result of heat transfer from the melt.

A steady power of 10 kW has been assumed for chemical vapor transport production in the mid 1990's, and 7 kW for directional solidification. This power is required primarily as heat. It can, in general, be interrupted for periods on the order of minutes.

Biological Materials

The usefulness of a wide range of biological materials depends on the degree to which they can be concentrated and purified. Current terrestrial processes for separating these materials are often limited by convection. The materials are purified by flow processes in aqueous solution. The sharpness of the flow patterns is degraded by thermal and buoyancy-driven convective forces. This lack of resolution limits the purity of the separation products. Elimination of convective forces can greatly enhance the sharpness with which different materials can be separated, as well as increasing the concentration of the product. The improved separation of pharmaceuticals that can be achieved in space offers a near-term commercial product of space-based materials processing. Two processes have been considered for this application: continuous flow electrophoresis and isoelectric focusing.

Continuous Flow Electrophoresis (CFE)

Biological materials, such as proteins, enzymes, and cells often have a surface electric charge distribution which causes them to respond to an electric field. When placed in a fluid medium with an electric potential difference between two ends, these materials will be transported toward one end. The speed with which the materials travel varies according to the charge distribution. Different materials have different mobilities. This difference in mobility allows different materials to be separated according to their electric charge distribution.

Figure 3-6A shows conceptually how a continuous flow electrophoresis apparatus works. A liquid buffer solution is located between two electrodes. A potential difference between the electrodes establishes an electric field in the solution. Those components of the material to be separated which have the highest electric mobility move the fastest to one electrode. After some time in the field, the various components of the material are separated. On Earth, buoyancy-driven convection caused by concentration differences and by density changes due to Joule heating limits the size of the sample which can be separated. Typically, samples of less than 0.1 ml are separated on a porous gel plate by a batch process

Figure 3-6A

CONTINUOUS FLOW ELECTROPHORESIS

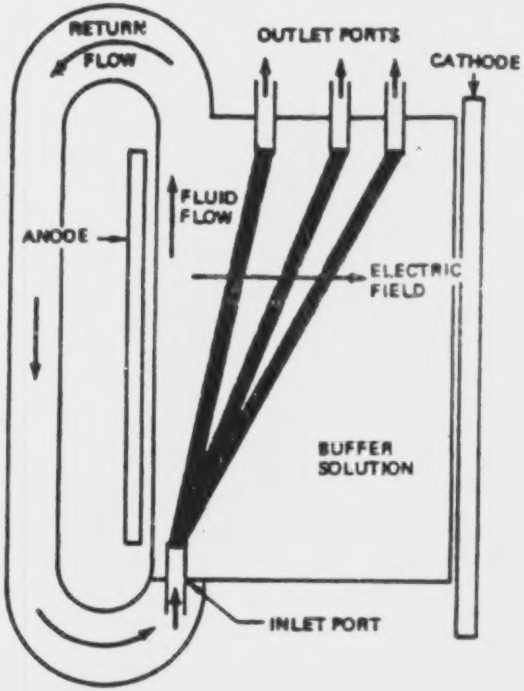

RETURN FLOW
OUTLET PORTS
CATHODE
FLUID FLOW
ANODE
ELECTRIC FIELD
BUFFER SOLUTION
INLET PORT

Figure 3-6B

McDonnell Douglas electrophoresis processing machine is checked by corporate payload specialist Charles D. Walker prior to operating the unit on the orbiter Discovery's first flight. The sample material is injected into the column near the bottom of the vertical glass plate and flows upward in a buffer solution. As the material moves up the column, an electric field separates the material more precisely than can be done on Earth.

Aviation Week & Space Technology, June 25, 1984 where the samples are frozen into place after some period in the chamber. The small size of the apparatus limits the separation resolution, while convection considerations limit the possible purity of the product.

Elimination of gravity-driven convection in orbit allows a continuous flow CFE. In CFE, the buffer solution flows continually perpendicular to the electric field, while the sample is also added continuously to the processing chamber. Much larger volumes of sample materials can be separated in this manner with much larger processing chambers. As shown in Figure 3-6A the product materials are collected in distinct collection vials. The continuous processing, larger volume, longer time in the electric field, and lack of convection allows a much higher flow rate of materials throughout, higher yield from a given quantity of sample material, finer separations, and higher purity of product material than can be achieved on Earth, thus greatly enhancing its medical and economic worth.

Space-based electrophoresis experiments were first attempted during the Apollo program with unclear results due to poor experiment design. The first successful results were obtained in the Apollo-Soyuz spacecraft. In this experiment, in which material was separated by a batch process in a small column and frozen in place, the degree of separation of human fetal kidney cells was much higher than any previous results. As a result, distinctions were found between three different cell types that had not previously been identified. This development program has now accelerated with the introduction of the Shuttle. A partnership has been formed with McDonnell Douglas to develop a commercial CFE process under a Joint Endeavor agreement with NASA. Results of experiments conducted on STS-4 were highly reassuring, and three more experiments have been flown in 1983. Figure 3-6B is a picture of the latest continuous process machine flown on the STS 41-D mission in August 1984.

Isoelectric Focusing

A similar technique which has been proposed for space-based separation of biological materials is isoelectric focusing. The buffer solution establishes a pH gradient when the electric field is imposed. Since the mobility of the material to be separated varies as the pH of the buffer, the sample material moves in the direction of the gradient to a particular value of the pH: the isoelectric point. The products are well-focused within the pH gradient and then collected as in continuous flow electrophoresis. This method may have potential for even finer resolution than electrophoresis, but has not yet been demonstrated in space. Since the pH environment of isoelectric focusing is extreme, it is not suitable for processing living cells. Three experiments are scheduled for hormone purification on a Space Shuttle mission in 1984.

The power requirements for space station accomodation of biological separation processes are generally smaller than for semiconductor growth, especially since the temperatures are very low. The need for refrigeration to preserve samples imposes special thermal control constraints.

The continuous flow electrophoresis process is currently the most advanced Materials Processing Science (MPS) program. The success of the Apollo-Soyuz experiment, an extensive ground-based research program, and especially the STS-4 mission has resulted in a firm belief that the concept is understood well enough to do engineering design. McDonnell-Douglas Astronautics and Ortho Pharmaceuticals Division of Johnson and Johnson have joined forces and now plan to fly a production prototype electrophoresis unit in 1985, which will produce the first commercial product. Their development program apparently calls for a fleet of unmanned, shuttle-tended free-flyers beginning in 1986. Although specific plans are proprietary, it seems reasonable to project attaching these automated factories to the Space Station when it becomes available. This would allow the use of space station power and control systems, as well as facilitating materials storage, delivery, and retrieval by operating through a single central base.

A large number of biological products has been proposed for space station separation. A recent forecast of the potential for beneficial space-produced pharmaceuticals and the number of patients that could benefit annually is shown in Table 3-1.

Table 3-1

EXAMPLES OF BENEFICIAL BIOLOGICAL PRODUCTS

PRODUCT	PRODUCT OBJECTIVE	CURRENT STATUS
GROWTH HORMONE (850,000)*	STIMULATES JUVENILE BONE GROWTH, PROMOTES HEALING OF ULCERS	RESEARCH QUANTITIES, LOW PURITY
BETA CELLS (3,200,000)	SINGLE INJECTION CURE FOR DIABETES	CLINICAL QUANTITIES NOT SEPARABLE
α- ANTITRYPSIN (500,000)*	LIMIT EMPHYSEMA DISEASE STATE, ENHANCE CANCER CHEMOTHERAPY	RESEARCH QUANTITIES, LOW PURITY
EPIDERMAL GROWTH FACTOR (1,100,000)*	SKIN BURN AND WOULD HEALING	RESEARCH QUANTITIES, LOW PURITY
INTERFERON (20,000,000)*	VIRAL INFECTION IMMUNITY	LOW YIELD AND PURITY
ANTIHEMOPHILIC FACTOR (15,000)*	ELMINATE IMMUNOLOGICAL REACTIONS FOR HEMOPHILIA	LOW PURITY AND LOSS OF BY-PRODUCTS

* ANNUAL PATIENT LOAD - U.S. MARKET

The power required to process sufficient material by electrophoresis to satisfy this demand in the mid-1990's has been estimated to be 15 kW. Isoelectric focusing of additional materials is assumed to add another 4 kW. This power is primarily that required to maintain the electric field in the apparatus, which must be DC power. Other power consumers are for refrigeration of the biological materials and for fluid pumping. These uses are likely to be for AC power.

Glasses and Fibers

The reduced gravity in orbit allows materials to be processed in a container-free environment. First, fluids under microgravity conditions form large globules that "float" in space without spilling or breaking up. This allows the possibility of melting and resolidifying materials without the materials ever contacting the container walls while in the molten state. This property might be useful for a variety of material classes, the most hopeful class being high quality and unique glasses. Second, glasses are distinguished from metals and other solids by their lack of crystalline structure. Under gravitational conditions, molten glass tends to solidify around nucleation sites at the crucible walls as it cools because the walls are cooler than the interior of the melt and the impurity level is higher there. Crystals tend to grow around these nucleation sites, resulting in a higher degree of crystalline structure than is desirable. In a containerless environment, a higher degree of supercooling is possible without the onset of heterogeneous nucleation, thus allowing a lower level of crystalline structure and therefore more ideal glassy properties. Homogeneous nucleation also allows the processing of glasses with different chemical mixes than are possible on Earth. So containerless processing generates more ideal glassy properties and should induce unique glasses to form which cannot be duplicated on Earth.

A facility for processing glass in space will be dominated by the furnace. The furnace has two primary elements: a programmable power supply for heating and a positioning control system for maintaining the melt in place. The material sample would likely be heated by adsorption of electromagnetic radiation, most likely in the microwave or infrared frequency range. Other heating mechanisms that have been proposed include electron beam impingement and solar concentrators. Although the melting temperature of most of the candidate glasses is very high, the actual heating power load can be quite low because containerless processing eliminates conductive and convective heat losses. A kilogram sized specimen of silica glass can be melted in about a half hour with a 1 kW heating source. Heat losses can be further minimized by using infrared reflecting walls. A glass specimen would be heated to a few degrees superheat and then rapidly cooled by intense radiation to the walls to promote homogeneous nucleation.

The heated samples tend to drift in space due to orbital dynamics and "g" jitter if they are not actively held in place. They can be positioned by several means. They can be attached to a thin rod which holds them in place by surface tension. This method may result in heterogeneous nucleation and conductive heat loss to the rod. If the samples can be allowed to come in contact with a cover gas they can be held in place by acoustic pressure driven by loudspeakers in the walls of the chamber. Truly containerless processing in a vacuum can be achieved by positioning the sample with either uniform electromagnetic or electrostatic forces that surround the sample.

Uses for space-processed glasses will likely be restricted to those for which high purity is essential. These might include optical fibers with high transmissivity which would require fewer repeaters than current systems, and allow faster, more efficient data transmission. Optical fibers are finding increasing use where higher data rate and more compact data transmission are desired and where resistance to electromagnetic interference is demanded.

Specialty glasses which might benefit from space processing include optical filters, where particular spectral bands are to be suppressed, and lead glasses for viewing radioactive substances. Another common use is for laser host materials, such as neodymium-doped YAG. It seems likely that many more applications would develop once space-based processing demonstrates the formation of glass forms that could not be reproduced on Earth. Optical glasses for lenses and mirrors might be processed in space with very low crystallization, which would provide higher quality image processing.

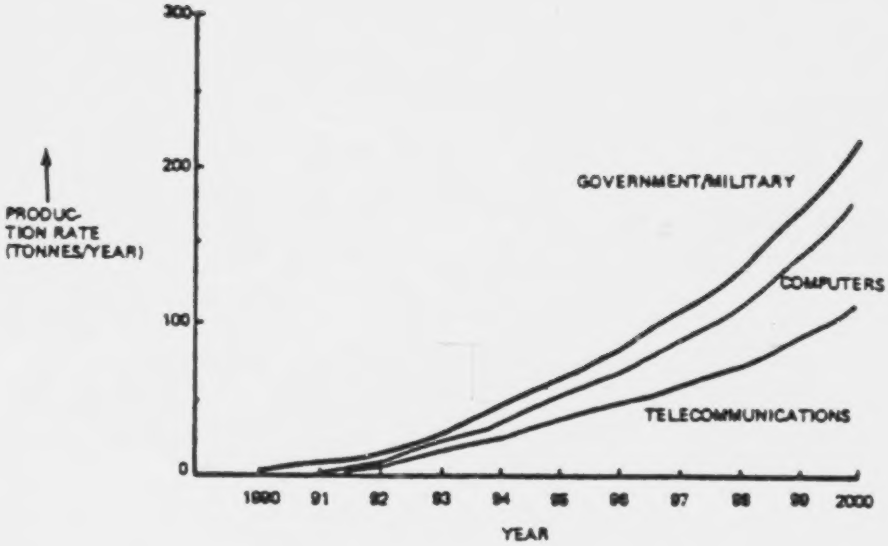
No containerless processing of glasses has been done by the United States in space. Projections of future demand have been based on expected properties of micro-g containerless-processed glass, not on space experimental results. Until space experiments have been completed and the results evaluated, it will be difficult to foresee a commercial market. A more plausible development scenario would start with at least a four or five year experimental research program where different glass materials would be formed by different cooling processes and examined. An orderly research program would establish the properties of different materials, the effects of experimental conditions such as sample temperatures, cooling rates, and positioning methods, and the efficiency of a variety of heating and cooling techniques. Once this basic research program has advanced our knowledge of space-processed glasses and their fabrication techniques, it may be easier to identify commercial markets with some understanding of costs and benefits.

Assuming a basic research program begins soon and is supported at a reasonable level on a continuous basis, commercial production might begin by 1990. An estimate of the rate of production of space-produced glass was based on a recent estimate of market projections of optical fiber components through 1990, and on the assumptions that space processing will offer significant improvements in fiber quality. An estimate of the production rate of space-processed optical fibers is shown in Figure 3-7.

Without a specific process for producing containerless-processed optical fibers, it is difficult to project space station accomodations. Reasonably consistent assumptions can be made, however, to make rough order-of-magnitude estimates. Here we assume that a single containerless glass furnace has an electric heater and a radiofrequency positioning system. We further assume that a molten source of glass has a mass on the order of 1-3 kilograms and that this source is fed continuously and 100 fibers can be pulled simultaneously from the source and stored on spools. If the pullers draw 10 μm diameter fibers at 1 m/s with an 80% availabil-

Figure 3-7

ESTIMATED SPACE- PROCESSED OPTICAL FIBER PRODUCTION RATE



ity, then a single such furnace would produce 434 kg/yr while consuming about 50 watts of electric power. Assuming that the glass is packaged into the orbiter with a 1.5:1 structure ratio, the demand throughout by 2000 requires 340 furnaces.

With these speculative Boeing estimates, the electrical power demand can be scaled. The power grows steadily with each flight, reaching about 5-6 kW by 1994-96 and 17 kW by 2000. This power can be AC or DC, but interruptible only for short periods.

Commercial Materials Processing Science (MPS)

The preceding materials processing missions represent some of the potential commercial enterprises at this time. It is the nature of commercial enterprise during the early investigation of concept phase that specific market areas and magnitudes are speculative estimates. The NASA reference missions set is a reasonable scenario of mission development based on current knowledge of projected product demand, current understanding of microgravity processes, and estimates of future development of competing processes. It is possible, even likely, that the actual commercial materials processing mission set in the 1990's will be significantly different than currently projected; some of the missions projected today will not become commercial successes and other missions not yet conceived will be successul ventures. No doubt the early projected power requirement scenarios were limited by the arbitrary ground rules of only 20 kWe per year per mission.

Although specific details of the commercial MPS mission set cannot be confidently predicted, the NASA reference set represents a reasonable projection based on current knowledge and credible assumptions. A number of generalizations can be made of likely market trends. For instance, it is clear that any commercial process must develop through the various phases discussed above. Any new process under development will likely consume at least one kilowatt during the verification of concept phase and more during the engineering demonstration phase, eventually growing at 2-10 kW/yr once a commercial market is established. If new materials and processes are to be developed, then sufficient power must be made available to progress through the pilot/prototype phases. If a number of processes are to be developed as the commercial opportunities are seized, then a surplus of power must be available to test these processes. This means that whatever power level is required to satisfy the demand of existing missions, additional power is necessary if new commercial missions are to be encouraged. If the space station power level is determined by assessing the requirements of predefined missions, then the commercial MPS market volume will become a self-fulfilling prophecy. There will always be just enough power available to satisfy the requirements of the planned mission set, and never enough to develop new missions. Although this might be a satisfactory approach to fulfilling the requirements of a pre-planned program, it would not satisfy a market-driven commercial demand. The commercial attractiveness of materials processing in space therefore depends to a large extent on the availability of ample power beyond that which is committed to established missions.

Additional Mission Factors

The magnitude of the electrical power load is not the only factor that tends to favor a nuclear power source for space station missions to supplant the initial solar power systems. Other beneficial factors are summarized below.

- System readily scaleable to high power levels
- Power generation system size independent of orbit
- Potential elimination/minimization of exclusion volumes
- Insensitivity to shadowing from large structures
- Low drag
- Controllability
- Insensitivity to natural environment

Since a solar power source can only generate power while it has solar radiance incident on it, the arrays must be sized to supply energy storage for nightside use. This is done with either battery or regenerative fuel cell energy storage for photovoltaic systems. Solar dynamic systems employ molten salts. The storage device is charged by the primary power supply on the sunlit side of the orbit and discharged by electrical load on the dark side of the orbit. The arrays, and most of the power conversion and conditioning equipment, must be sized for a considerably higher power than simply that of the load. They must be sized for the mission demand, attrition due to age, energy storage, and ineffeciencies of the energy storage/discharge system. Thus a solar system with a 100 kWe total load might have to generate 200 kWe on the sunlit side of the orbit. This is not true of a nuclear power system, where the power level is independent of orbit consideration.

3.3 Space Station Configuration Options

In order to study the impact of the nuclear electric power system on the Space Station and to conduct trade studies of reactor-powered space station configurations, it was necessary to select a reference space station concept. At the time of the study there was a wide variety of architectural concepts still being considered by the Concept Definition Group (CDG).

The concept selected as the reference Space Station for this nuclear space station study is of a class of concepts referred to as "gravity gradient concepts", related to the "power tower" geometry of Figure 3-8. It is also the concept currently being employed by NASA. The gravity gradient stabilized space station concept was selected because it was judged to be the concept most amenable to the addition of a nuclear reactor system after starting initially with a solar powered station. A 75 kWe net deliverable power design is shown here. This judgement was based on looking ahead at the potential reactor and radiator configuration, and their integration requirements. This selection did not result from a thorough evaluation of the configuration options and is not to be construed as a recommendation for the space station design; it merely serves the purpose of assigning a common data base for a comparison of the various reactor-space station configurations.

The configuration options for safely including a reactor as the power subsystem for a space station are discussed in the following sections.

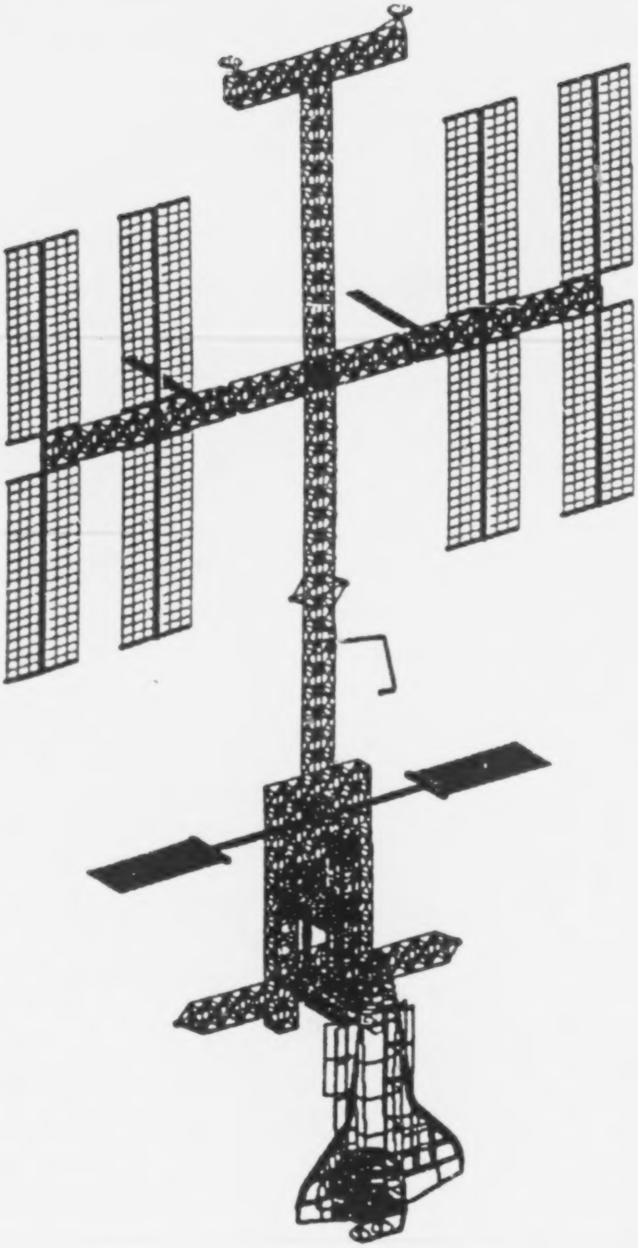


Figure 3-8 Space Station, "Power Tower Concept"

The options include: attaching the reactor rigidly to the space station; attaching the reactor to a flexible tether; or locating the reactor on a free-flying spacecraft removed from the space station. Power transmission can be achieved by electrical conduction, by fuel transport, or by electromagnetic beaming. Fourteen different configuration options were investigated, and three were selected for more detailed trade studies.

The configuration options can be categorized according to the location of the reactor and the mechanism by which power is transmitted to the space station. The complete option tree considered in this study is shown in Figure 3-9. The reactor, shield, power conversion system, and radiator designs were considered on a generic basis in this preliminary assessment, i.e. general system advantages and disadvantages were investigated rather than focusing on subsystem designs. The power level was also not initially defined in this systems assessment, but a value between 100 kWe and 300 kWe was implicitly assumed early in the study. Also shown in Figure 3-9 are three of these options (encircled) that were selected for detailed study, and are described herein.

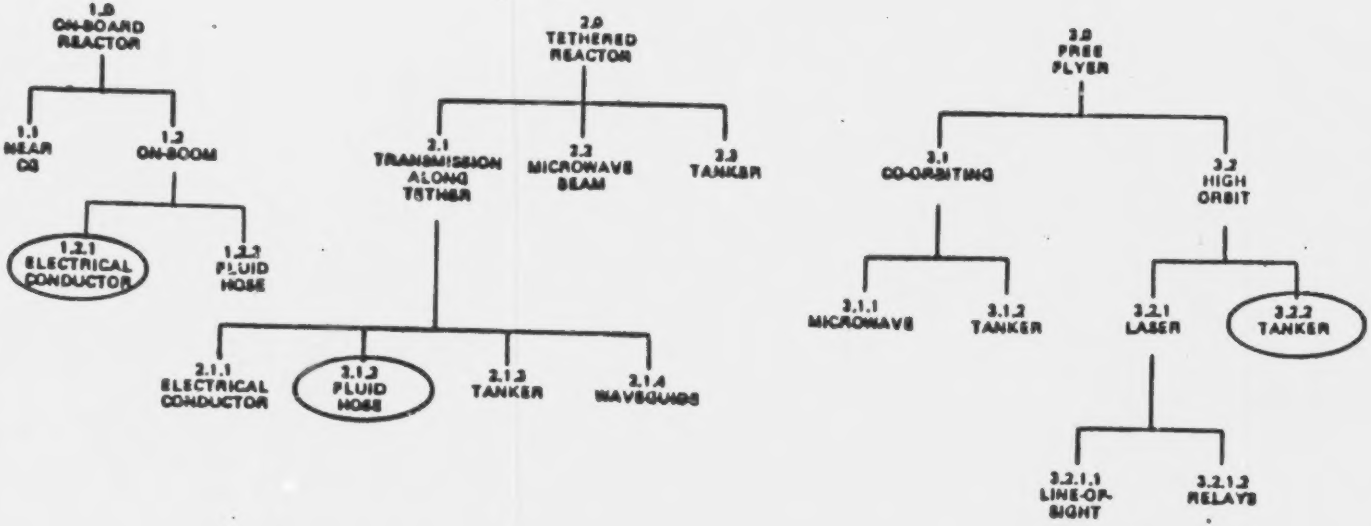
Reactors which are rigidly attached to the space station can be located either in the space station itself or on a boom. The space station electrical power can be drawn from the power plant either directly through conducting wires or indirectly as in a regenerative fuel cell. The indirect method consists of an electrolysis plant located with the reactor and fuel cells located with the space station. Fuel cell reactants would be pumped through fluid pipes located in the boom structure to the fuel cells, with a return line pumping the reaction products back to the electrolysis plant.

Reactors which are attached to the space station with a long, flexible connection are tethered reactors. Power transmission can be either along the tether or through free space. The tether can be electrically conducting with reactor-generated electricity transmitted through the tether. With an electrolysis plant located with the reactor, the fuel cell reactant can be transferred either continuously through flexible hoses or with a batch process using tanks transported either along the tether ("clothes

Figure 3-9

Reactor-Space Station Configuration Options

KSP-101


1.0 ON-BOARD REACTOR
1.1 NEAR CG
1.2 ON-BOOM
1.2.1 ELECTRICAL CONDUCTOR
1.2.2 FLUID HOSE
2.0 TETHERED REACTOR
2.1 TRANSMISSION ALONG TETHER
2.2 MICROWAVE BEAM
2.3 TANKER
2.1.1 ELECTRICAL CONDUCTOR
2.1.2 FLUID HOSE
2.1.3 TANKER
2.1.4 WAVEGUIDE
3.0 FREE FLYER
3.1 CO-ORBITING
3.2 HIGH ORBIT
3.1.1 MICROWAVE
3.1.2 TANKER
3.2.1 LASER
3.2.2 TANKER
3.2.1.1 LINE-OF-SIGHT
3.2.1.2 RELAYS

line") or through space. Electricity generated at the reactor can also be converted to electromagnetic energy and beamed to the space station, either through free space or through a waveguide.

Free-flying reactors can be either in the same orbit as the space station or in a higher nuclear-safe orbit. If the reactor is coorbiting, power can be transferred either by microwave beaming or by fuel tankers. If the reactor is in a higher orbit, then the reactor and space station are not always near each other. A fuel tanker can still be used to transport fuel cell reactants and reaction products back and forth, but electromagnetic beaming must be in the line of sight in the visible spectrum. Laser power transmission can be used in conjunction with an energy storage device or with relay satellites. If beaming is only done when the reactor and space station are in direct line of sight, then energy must be stored for use when the Earth occults the direct path. With a sufficient number of relay satellites, energy can be beamed continuously from the reactor to the space station.

3.4 Nuclear Electric Power Systems

On-board Reactor Selection

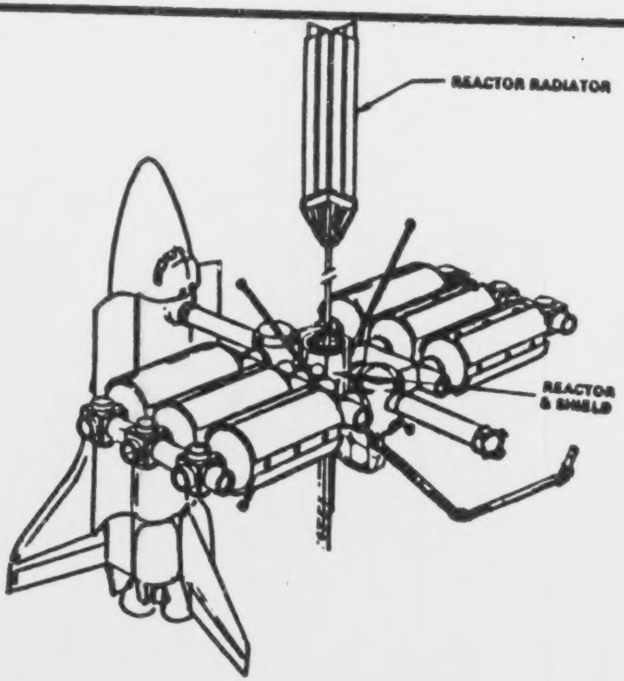
The most straightforward configuration option is that where the electrical power is generated near where it is to be distributed. This option places the reactor on the space station with sufficient shielding to allow space station personnel safe radiation dose rates for continuous residence on the space station. This option is referred to as "submarine" option because of its commonality with a nuclear power plant on a manned submarine.

This concept is illustrated in Figure 3-10. The reactor, power conversion system, and shield are located on the space station, with the radiator somewhat removed from the station. A 100 kWe space reactor will reject from 300 to 2000 kW of heat at temperatures in excess of 550° K, with details dependent on the power conversion design. This heat will be rejected by radiation from 40-80 m^2 radiators. To prevent excess heating of the space station and astronauts performing extravehicular activities,

Figure 3-10

Reactor Near Space Station CG

NSP-137



- Best space station attitude flexibility
  - High ballistic coefficient
  - Stable configuration
- Heaviest shield mass
  - 40 – 50 tonnes system mass with 3-meter exclusion distance
- Allows full EVA range
  - Easy maintenance
- Requires separation of radiator from reactor
  - Fluid pumping
  - Single point failure from pipe break
- Minimum transmission line distances

the radiator must be removed to some distance from the space station, probably 30 meters or more away.

This approach requires pumping of a heat transfer fluid from the reactor to the separated radiator. It also has the heaviest shield mass of all the options considered, since the shielding must protect people residing in close proximity on a continuous basis. The shield mass required to reduce the radiation dose rate to 5.7 mrem/hour at a distance of 3 meters from the reactor in all directions is about 35-45 tonnes, depending on power level and conversion system.

On the positive side, this approach allows the most flexibility in space station attitude, since there is no dominant inertia moment. It has a very high ballistic coefficient, requiring a minimum of orbital makeup propulsion. This configuration also allows a wide envelope of EVA operations. This envelope is not constrained in any direction by ionizing radiation levels. The only EVA constraint is that due to thermal exposure near the radiators. This option provides good opportunity for manned maintenance of the reactor system if that requirement is desired.

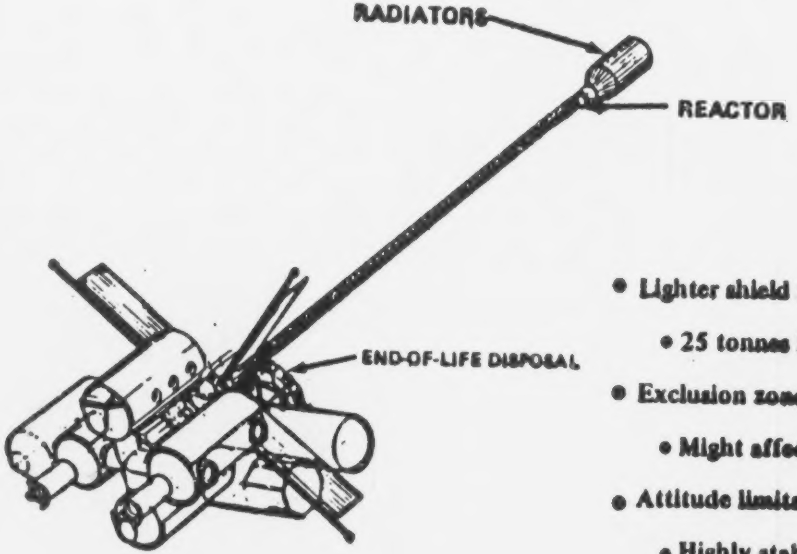
The shield mass can be reduced by placing the reactor on a boom attached to the space station, as shown in Figure 3-11. Rather than shielding for continuous manned presence close to the reactor in all directions, this option requires shielding for limited exposure periods in all directions near the reactor and continuous exposure only on the space station, which is removed to some distance away from the reactor. This reduces the shield mass to 12-20 tonnes, depending on distance, power level, and conversion system. This option also places the radiator near the heat source, reducing the need to pump heat.

The boom-mounted reactor option achieves its mass savings by restricting personnel access around the reactor, allowing lighter shielding. Exclusion zones are therefore introduced within which EVA and orbiter traffic is restricted to limited duration. This might affect reactor maintainability if the design requires manned maintenance. The boom-mounted reactor also introduces a preferred space station attitude.

Figure 3-11

Reactor On Boom

MSP-138


RADIATORS
REACTOR
END-OF-LIFE DISPOSAL

- Lighter shield mass
  - 25 tonnes lighter
- Exclusion zones
  - Might affect maintainability
- Attitude limitations
  - Highly stable gravity gradient mode
- Requires power transmission
- Radiator near heat source

The large mass at the end of a long boom will drive the system toward a highly stable gravity gradient mode. Since electric power transmission over the same 70 meters of boom length (optimized trade-off of shield weight versus boom length and weight) required only a 5% power penalty, it was selected as the preferred study option over the fluid hose approach.

Tethered Reactor

The tethered reactor option selected for study is shown pictorially in Figure 3-12. The complete nuclear electric power system is located at the free end of a 30 kilometer flexible tether connected to the Space Station at the fixed end. Nuclear safety considerations dictate a 30 km tether such that if the tether had to be severed the NEPS would, by the gravity gradient-induced tension, passively rise to about a 700 km, 300 year nuclear safe orbit when an orbit-circularizing burn is added. In this selected configuration, power transmission is by transfer of fuel cell reactants (water, hydrogen, & oxygen) through hoses.

One drawback to a long tether is the resulting acceleration imparted to the space station. The reactor-space station system will travel in an orbit corresponding to a balance of forces at the system center of gravity. Pseudogravitational forces will not cancel. The strength of these forces is about 3.7×10^{-4} m/s^2 for each meter away from the center of gravity, or 400 micro-g's per kilometer.

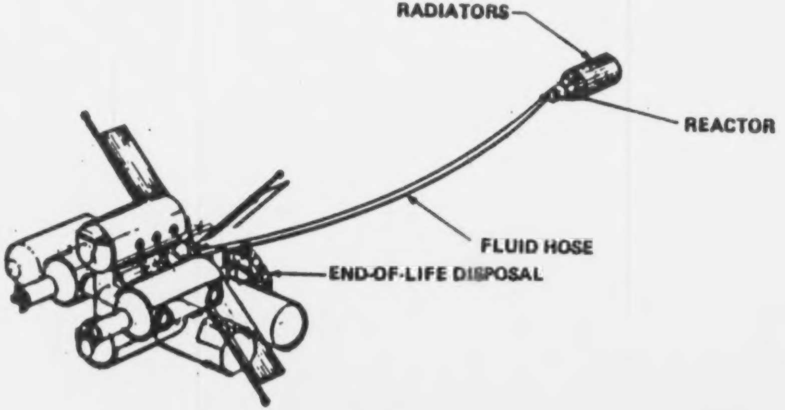
Many of the reference space station missions require microgravity conditions for materials processing. While it is not yet well-known what level of acceleration is acceptable to complete these missions, it is believed that g-levels between 10^{-5} g and 10^{-3} g may be required. If the missions are sensitive to 10^{-5} g (10^{-4} m/s^2), then a tether length of 50 meters or more would perturb the mission. If 10^{-3} g is allowed, then 5 kilometer tethers would be acceptable. Shorter tethers in the 60 to 70 meter range have reached the optimum safe separation distance and provide no advantage over the fixed boom case previously discussed.

In this option the NEPS has an electrolysis plant associated with it, and fuel cells on the space station. This is shown schematically in

Figure 3-12

Tethered Reactor

MSP-139


RADIATORS
REACTOR
FLUID HOSE
END-OF-LIFE DISPOSAL

PROS	CONS
DECREASED SHIELD MASS	ASYMPTOTIC ≥ 60 m
DISTANT RADIATOR	GRAVITATIONAL FORCES $\sim 0\ (0.06\ \frac{\mu g}{m})$
REDUCED TRAFFIC CONSTRAINTS	SINGLE POINT FAILURE FROM TETHER BREAK
OBVIATES PERIGEE KICK STAGE FOR LONG TETHERS	

Figure 3-13. The fuel cell reactants have a high systems synergism when hydrogen-oxygen fuel cells are used. The reactor would then provide oxygen for life support systems, hydrogen for stationkeeping propellant, and perhaps fuel for cryogenic orbital transfer vehicles. The reactant flow rate required for 100 kWe is 8-10 gm/s for fuel cell efficiencies of 60-80%. Assuming a regenerative fuel cell system efficiency of 60-75%, the reactor output power must be 1/3 to 2/3 higher than the load required at the space station.

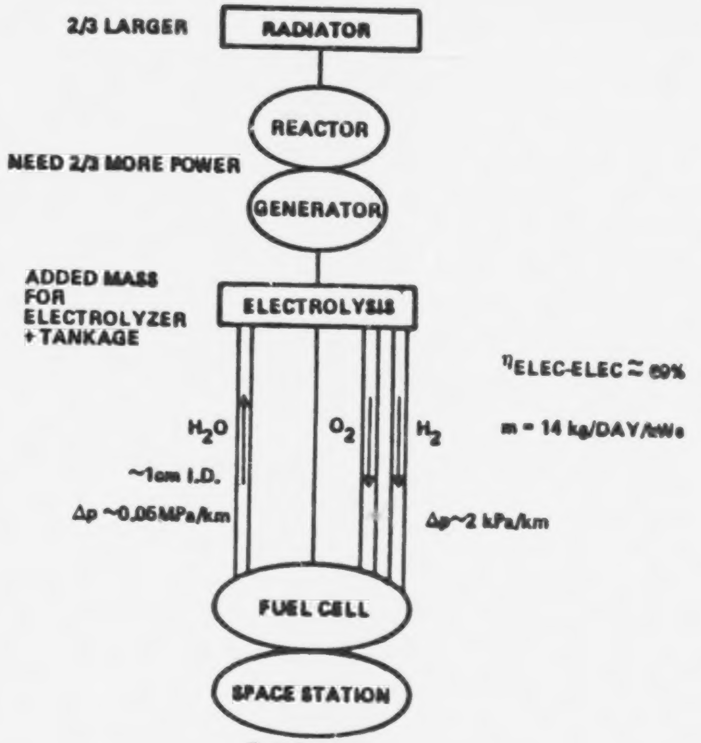
The reactants are to be carried to the space station through hoses on a continuous basis, with hydrogen and oxygen gas flowing to the space station and water returning to the reactor.

Power can also be transmitted to the space station in the form of microwave beams. A klystron at the reactor generates microwaves which are transmitted to the space station, either through a waveguide or through free space. Klystron efficiencies of 35% have been measured, and optimistic projections estimate efficiencies of 70% may be possible. Antenna efficiencies are likely to be about 50%, but optimistic projections may place this value as high as 90%. Waveguide attenuation coefficients between 0.01 and 0.03 decibels per meter seem likely, while beam losses of 20-40% are reasonable for S-band (3GHz) transmission through kilometer distances. Thus, the range of reactor output required to deliver 100 kWe to the space station for the free space microwave beaming option is 200-950 kWe. For a one kilometer waveguide tether, reactor outputs of 1.6 MWe-6MWe are required.

The fluid hose tether provides continuous fuel in an untended mode of operation and involves no cryogenic fuel. It might be vulnerable to meteoroid impact and must have provisions to locate and repair leaks. Of all the tether options, the fluid hose requires the least reactor power. The fact that the fuel cell options provide high system synergism and fair system efficiency led to the selection of this for study over the microwave options. The fact that the fluid hose provides fuel on a continuous basis and does not require a liquefaction plant or crew-monitored traffic management led to the selection of the fluid hose as the most favored tether option for detailed trade studies.

Figure 3-13

Fluid Transport Tether


2/3 LARGER
RADIATOR
REACTOR
NEED 2/3 MORE POWER
GENERATOR
ADDED MASS FOR ELECTROLYZER + TANKAGE
ELECTROLYSIS
$\eta_{ELEC-ELEC} \approx 60\%$
H_2O
O_2
H_2
$\dot{m}$ = 14 kg/DAY/kWe
~1cm I.D.
Δp ~0.05MPa/km
Δp~2 kPa/km
FUEL CELL
SPACE STATION

FLUID HOSE

PROS	PROVIDES OTV FUEL PROVIDES LIFE SUPPORT OXYGEN REDUCES CRYOGEN TRANSPORT
CONS	METEOROID VULNERABILITY ADDED MASS OF ELECTROLYZER HOSES HIGHER POWER

Free Flyer Reactor

Figure 3-14 shows the Free Flyer NEPS option to install the reactor in an orbit in which most radioactive material will decay before reentry into the biosphere. Power transmission for this option was selected to be by water and fuel cell reactant tankers. Electromagnetic beaming is impractical because of the long separation distance since the free flyer platform and Space Station would "see" each other only about twice a year.

The principal advantages are the very low shield mass required since no manned presence is contemplated in close proximity, and elimination of the need to activate an orbital transfer booster to boost the NEPS at the end of its operational life. However, this independent platform must have all of the systems required of a complete spacecraft, including attitude control, communications, and power system control. Further, the savings in shield mass come at the expense of greatly reduced options of repair, maintenance, and/or changeout of life-limited components.

A schematic of the high orbit free flyer reactor option is shown in Figure 3-15. The reactor has an electrolysis and liquefaction plant, and the space station has a fuel cell. Liquid hydrogen and oxygen are stored in tanks at the reactor which are carried to the space station with orbital transfer vehicles. The OTV carries water to the reactor on the return trips. Since the propellant required for large plane changes is very large, the frequency with which the reactor and space station become coplanar determines the launch frequency and therefore the storage and payload mass. The orbital transfer ΔV and the payload mass determines the propellant requirements.

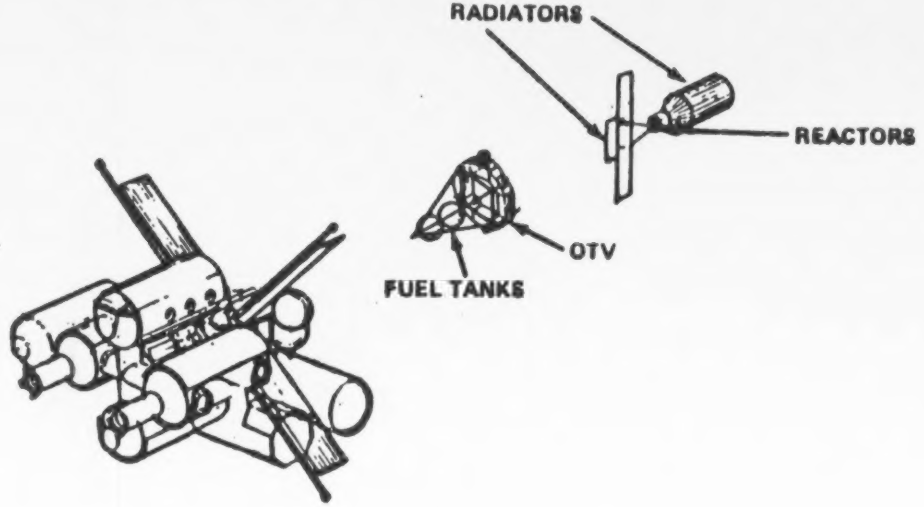
Mission/Space Station Sensitivity

Any design configuration selected must be capable of performing the intended missions. It must provide power to the space station in excess of current projected needs, largely for materials processing missions. It must provide good viewing for astronomy and Earth observations missions. It must allow extravehicular activity with considerable freedom of motion for space-based assembly and maintenance. It should not be subject to

Figure 3-14

Free-Flyer Reactor

NSP-140


RADIATORS
REACTORS
OTV
FUEL TANKS

ADVANTAGES

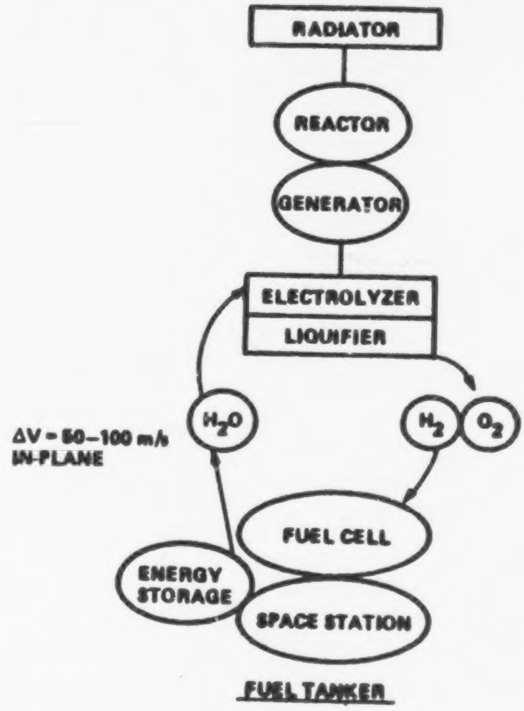
- NUCLEAR SAFE ORBIT CAPABILITY
- LIGHT SHIELD

ISSUES

- REQUIRES INDEPENDENT SPACECRAFT SYSTEMS
- REQUIRES POWER TRANSMISSION

Figure 3-15

High Orbit Free Flyer Option


RADIATOR
REACTOR
GENERATOR
ELECTROLYZER
LIQUIFIER
H_2O
H_2
O_2
ΔV = 50–100 m/s
IN-PLANE
FUEL CELL
ENERGY STORAGE
SPACE STATION
FUEL TANKER

PROS	INHERENTLY SAFE DISPOSAL
CONS	ORBIT COMPLEXITY NODAL REGRESSION $\Delta\Omega$ ~ 0.6°/DAY PROPELLANT LOSSES ADDED MASS OF ELECTROLYZER LIQUIFIER TANKERS FUEL STORAGE NO MANNED MAINTENANCE

large accelerations which would jeopardize microgravity quality for materials processing. The constraints imposed on vehicular traffic and the frequency and magnitude of docking disturbances should be minimal. Finally, since crew size is limited and crew time is valuable for mission performance, the power system should not require large amounts of crew time.

All three NEPS configurations or options are readily scalable in power level in the range from 100 to 300 kWe and above. All three have extremely low drag and control complexities when compared with solar power systems. They do not interfere with viewing in any direction, except for the boom-mounted reactor which only blocks a very small area (approximately 10^{-3} steradians, mostly due to the radiator). The free flyer NEPS allows the space station complete flexibility of attitude, while the tether and boom-mounted configurations will have a strong gravity gradient moment.

The designs of the boom-mounted and tethered reactor shields are specified for acceptable exposure at the space station and limited exposure closer to the reactor. This will introduce some restrictions to traffic near the reactor, but these are minimal. The thermal output of the radiator at high temperature will limit extravehicular access in the vicinity, which constrains extravehicular activity within some exclusion volume near the boom-mounted reactor. There are no EVA constraints on the space station missions in the free flyer configurations, and only the obvious traffic restriction of avoiding collision with the tether in the tethered reactor case.

Microgravity quality is very high in both the boom-mounted and free flyer cases. The tethered reactor would induce an acceleration on the space station on the order of 0.05 m/s^2 (5 milli-g). This might adversely impact materials processing missions. If it does, then other designs would have to be considered, such as locating materials processing facilities at the center of gravity along the tether or providing a counter balance below the space station to move the center of gravity down to the station.

The free flyer reactor will have tanker traffic between the reactor and the space station ferrying fuel back and forth. This will cause docking disturbances and will occupy crew time in rendezvous, docking, fuel transfer, and return. There will also be additional orbiter traffic and docking to provide OTV propellant for the tanker. The OTV will also likely require periodic servicing at the space station, further occupying crew time. There will be no docking disturbances or crew time associated with the boom-mounted or tethered reactor options.

3.5 Descriptions of Specific Configurations

Based on the results of shield mass optimization calculations for the "on-board" approach to a safe nuclear power system installation and subsequent spacecraft tradeoff studies, three configurations of electric power system-space station integration were identified for continued evaluations:

1. A boom-mounted power system located 70 meters from the station;
2. Power systems tethered to but operating at a distance of about 30 kilometers from the station;
3. A free-flying power system operating in an orbit of about 700 kilometers. The Space Station orbits at about 500 kilometers.

For each of these configurations, a baseline power system delivering a net of 150 kWe to the Station was assumed early in the study before aggregate mission power levels were assessed, and was assumed to be provided by the baseline SP-100 thermoelectric nuclear electric power system of about 5 percent efficiency. A similar set of evaluations was performed for each of the power system-space station configurations assuming a net power requirement of 300 kWe supplied by an advanced dynamic conversion cycle (Stirling) of higher efficiency. This became necessary later in the study when the projected power requirements for missions alone approached 250 kWe as shown in Figure 3-1. These power conversion systems were selected for illustrative purposes only, and no attempt was made in this study to optimize performance.

Boom-Mounted Configuration, 150 kWe

A layout of the 150 kWe boom-mounted reactor power system is presented in Figure 3-16. In this configuration, the electrical power is delivered to the space station via aluminum cables. The 70 meter boom length was established by determining a minimum overall weight of reactor power system plus cabling as a function of boom length. With shorter booms, the increase in shield weight would be greater than the weight savings in the conducting cable, with reverse conditions occurring with the booms longer than 70 meters.

As shown in Figure 3-16, a shield half angle of 22.40 degrees protects the space station at the 70 meter separation distance. The shield thickness within this angle is sized to achieve the 5.7 mrem/hr design dose rate in the station. The shaped four-pi shield geometry is slightly thinner on the sides and on the end away from the station to meet the flyby dose rate of 200 mrem/hr. The primary and secondary loop bays are located on the far side of the shield from the station in separate shield sections which, in theory, can be disconnected to provide for replacement of either the reactor assembly or the power conversion unit. The latter component, though not shown in Figure 3-16, is physically attached to the shield section containing the secondary loop bay.

The shield mass for the layout shown in Figure 3-16 is estimated to be 18,000 kilograms with the mass of the reactor plus power conversion an additional 1,650 kilograms.

Tethered Configuration, 150 kWe

The layouts of two distinctly different configurations are shown in Figures 3-17 and 3-18; a man-rated system in the former figure and a free-flyer instrument-rated system in that latter. In both systems, some of the electrical power generated is used in an electrolysis plant to decompose water into its hydrogen and oxygen components. The gases are then pumped through hoses which are grouped together to form the umbilical tether between the reactor power system and the station. At the station, the hydrogen and oxygen are recombined to generate electrical power when

Figure 3-16

Boom Mounted Configuration

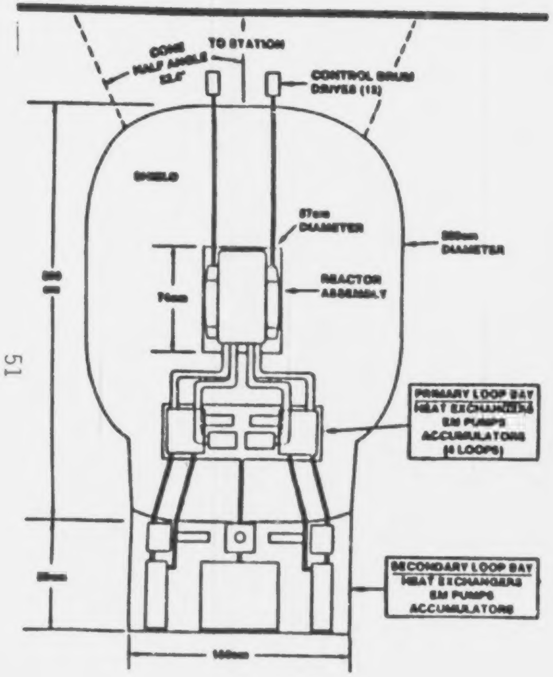

CONE HALF ANGLE 12.5°
TO STATION
CONTROL DRUM DRIVES (12)
SHIELD
87cm DIAMETER
REACTOR ASSEMBLY
74cm
PRIMARY LOOP BAY
HEAT EXCHANGERS
EM PUMPS
ACCUMULATORS
(4 LOOPS)
SECONDARY LOOP BAY
HEAT EXCHANGERS
EM PUMPS
ACCUMULATORS

Figure 3-17

Tethered Configuration

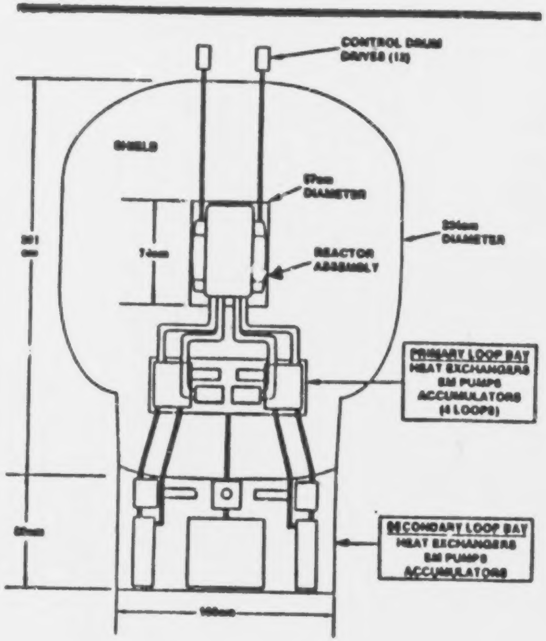
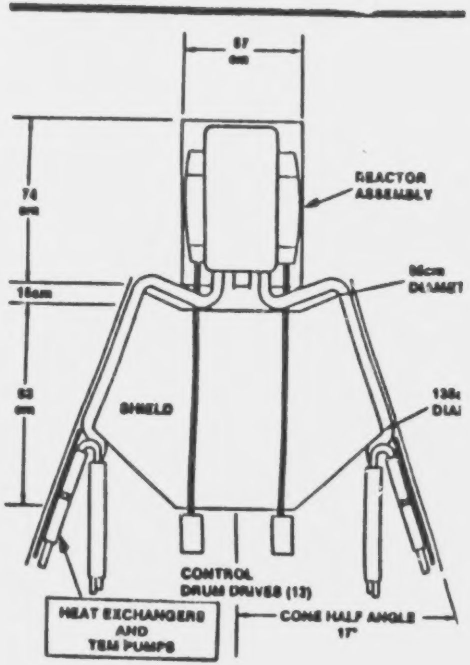

CONTROL DRUM DRIVES (12)
SHIELD
87cm DIAMETER
234cm DIAMETER
REACTOR ASSEMBLY
74cm
PRIMARY LOOP BAY
HEAT EXCHANGERS
EM PUMPS
ACCUMULATORS
(4 LOOPS)
SECONDARY LOOP BAY
HEAT EXCHANGERS
EM PUMPS
ACCUMULATORS

Figure 3-18

Free-Flyer Configuration


87 cm
74 cm
16cm
REACTOR ASSEMBLY
96cm DIAMET
SHIELD
136 DIA
CONTROL DRUM DRIVES (12)
HEAT EXCHANGERS AND TEM PUMPS
CONE HALF ANGLE 17°

needed, with the reformed water returned to the power system through tether ducts to complete the cycle. The power system is held by the tether under tension approximately 30 kilometers distance away from the space station in a higher altitude.

The man-rated tethered configuration of Figure 3-17 has a four-pi shield geometry that is sized to allow flyby approaches during power system operation, and manned maintenance in the power conversion unit and electrolysis plant after reactor shutdown. The primary and secondary loop design in corresponding shield sections is identical in function to the boom-mounted system because of the power required to run the electrolysis plant. This higher gross power is reflected in the slightly heavier masses for the shield and power conversion components.

The instrument-rated free-flyer configuration of Figure 3-18, when employed in a tethered mode, has a shield mass that is only five percent of the mass of the man-rated configuration. This is due to its conical shield geometry with a cone half angle of only 17 degrees and a much higher allowable dose rate. This type of shadow shield precludes manned approach to the power system so the dose rate is determined by tolerances of instrumentation located approximately twenty-five meters away from the shield. Thus, a very substantial savings in power system mass is realized for the disadvantage of excluding manned maintenance of the power converter and electrolysis plant.

Free-Flyer Configuration, 150 kWe

As noted above, the free-flyer configuration of Figure 3-18 is very similar in shape and internal arrangement as an instrument-rated tethered configuration in that a conical shadow shield geometry is used to protect an unmanned power conversion system and electrolysis plant. A much larger electrolysis plant, hence more electrical power, however, is required in the free-flying configuration to provide propulsive fuel for a tanker which transports liquefied oxygen and hydrogen fuels from the power system to the space station. This configuration assumes that space qualified liquefication plants can be developed. The required electrical power of 360 kWe exceeds the capacity of a power system using a single 4 megawatt thermal reactor. Consequently, two of these 4 MWt SP-100 reactors, placed end-to-end in tandem arrangement, were assumed for study purposes only as the nuclear energy source for the system, even though a redesigned, single reactor of greater thermal energy output would result in a smaller mass for the overall system. The conical shield for the free-flyer configuration is considerably larger than the conical shield of the tethered configuration because of the two reactor arrangement, the higher total reactor power level, and the larger area payload (power conversion subsystem plus electrolysis plant) to be protected.

300 kWe Stirling Power Conversion

The configuration evaluations described in the three preceding sections for 150 kWe net power output were repeated for assumed net power requirements of 300 kWe. To produce this quantity of power from an SP-100 reactor it was considered necessary to assume the use of more efficient advanced dynamic power conversion as represented by Stirling, Rankine or Brayton engine systems. Layouts for the boom-mounted, tethered, and free-flying configurations would be very similar to those shown previously. The main difference would be the substitution of four Stirling engine components for the heat exchangers in the secondary loop bays of Figures 3-16 and 3-17, and slightly smaller shield due to higher conversion efficiencies.

System Trade Summary

The results of the detailed trade studies on the three configurations are summarized in Tables 3-2 and 3-3, for 150 kWe and 300 kWe, respectively.

Although the charts show 1.5 Orbiter flights for an initial total mass of about 31.1 metric tons, including an OMV and emergency power, the boom-mounted NEPS for either the 150 and 300 kWe case actually requires only one (1) STS flight to place all of the NEPS equipment on board the Space Station. It is assumed in this scenario that the end-of-life boost vehicle (a modified OMV) and the emergency power kit will have been previously installed in the Space Station.

Table 3-2

TRADE TABLE

150 kWe at Space Station

THERMOELECTRIC, η = 5.1%	ON-BOARD (MAN-RATED)	TETHER (MAN-RATED)	TETHER (INSTRUMENT RATED)	FREE-FLYER (INSTRUMENT RATED)
INITIAL MASS IN ORBIT, tons	31.5	60.2	51.4	564
POWER LEVEL, MW_t	3	4.1	4.1	7.1
INITIAL VOLUME IN ORBIT, m^3	257	378	369	2790
STS LOGISTICS FOR IOC				
NUMBER OF ORBITER FLIGHTS	1.5	2.9	2.1	29
NUMBER OF OTV FLIGHTS	0	0	0	2
NUMBER OF OMV FLIGHTS	0	1	1	1
10-YEAR CUMULATIVE MASS, tons	32.4	84.3	68.5	1296
10-YEAR CUMULATIVE VOLUME, m^3	258	395	388	3560
CUMULATIVE STS LOGISTICS				
NUMBER OF ORBITER FLIGHTS	1.5	3.5	2.7	68
NUMBER OF OTV FLIGHTS	0	0	0	22
NUMBER OF OMV FLIGHTS	1	2	2	1

*MW_t = Reactor thermal rating, Megawatts

Table 3-3

TRADE TABLE

300 kWe at Space Station

STIRLING, η = 25%	ON-BOARD (MAN-RATED)	TETHER (MAN-RATED)	TETHER (INSTRUMENT RATED)	FREE-FLYER (INSTRUMENT RATED)
INITIAL MASS IN ORBIT, tons	31.1	77.6	61.1	1043
POWER LEVEL, MW_t	1.2	1.66	1.66	2.9
INITIAL VOLUME IN ORBIT, m^3	241	428	421	4640
STS LOGISTICS FOR IOC				
NUMBER OF ORBITER FLIGHTS	1.5	3.2	2.7	49.5
NUMBER OF OTV FLIGHTS	0	0	0	5
NUMBER OF OMV FLIGHTS	0	1	1	1
10-YEAR CUMULATIVE MASS, tons	31.9	94.2	77.7	2964
10-YEAR CUMULATIVE VOLUME, m^3	242	448	441	6752
CUMULATIVE STS LOGISTICS				
NUMBER OF ORBITER FLIGHTS	1.5	3.9	3.4	126
NUMBER OF OTV FLIGHTS	0	0	0	45
NUMBER OF OMV FLIGHTS	1	2	2	1

*MW_t = Reactor thermal rating, Megawatts

Because of the large tanker size and startup fuel inventory, and low efficiency, the 150 kWe free-flyer reactor option requires 29 Shuttle flights to get the system started. Once the system starts up, this option still requires two round trip OTV flights per year for fuel transfer plus four STS flights per year to provide propellant to the OTV. Selecting this option would result in considerable space station traffic and essentially a dedicated Space Shuttle and orbital transfer vehicle (OTV) for fuel production and delivery. There are alternatives available for reducing the number of shuttle flights, but these involve either a new launch vehicle or more OTV flights and do not change the basic conclusions that the free-flyer reactor involves many flights on a continuing basis.

The tethered reactor requirements lie between those of the other two cases. A 150 kWe tethered reactor system with an instrument-rated shield can be delivered in about two full STS flights and one OMV flight, with another 855 kg/year of water to be used for orbit makeup propellant. A man-rated shield would increase the mass by 17,800 kg, or 0.7 full orbiter bay equivalents, for the possibility of some manned maintenance of the power generation system.

To supplement the Boeing study, comparisons of solar photovoltaics, solar dynamic, and nuclear electric Space Station power systems were made by NASA-Lewis Research Center personnel. Preliminary in-house results show that over a 7 year life the total mass to orbit for 100 kWe solar PV and nuclear Stirling are about equal. However, at 250 kWe the solar PV total life cycle mass to orbit is 70,726 kg while the nuclear Stirling, including propulsion requirements, is 25,932 kg, *and as previously noted could be launched in just one Shuttle load.

3.6 Conclusions and Recommendations

Conclusions

- A nuclear electric power system is an excellent candidate for the Growth Space Station wherein power requirements are perceived to exceed 300 kWe.
- Station dynamics are simplified with a compact boom-mounted nuclear electric power system.

- There are no sun-orienting requirements nor energy storage provisions needed for the NEPS.
- The regenerative fuel cell subsystem can be fully integrated with the NEPS.
- The NEPS-on-a-boom with a high-efficiency Stirling conversion system is a viable, safe concept, requiring only one Shuttle flight to place it in orbit.

Recommendations

- An analysis should be made of concepts which allow for space station designs to provide for growth in the power system with time. The on-board distribution system should be designed to accomodate AC although the early DC powered station may convert in part to AC. To change from solar generated power to nuclear generated power, maximum use should be made of the original on-board electrical power system equipment, and studies made as to how the original equipment can be enlarged by adding modules.
- The design and operation should be examined to determine how the original solar array can be gradually disposed of when the growth power system is substituted. If portions of solar PV are stowed, it can be employed as the emergency power system.
- Since the SP-100 reactor power system design is not directed at this time to manned space stations, the reactor and shield technology will have to be researched to develop concepts of disposal and reentry. Venting will have to conform to the man-rated design. This may affect the reentry package design to meet the safety requirements of complete dispersal prior to ground impact.
- If the orbiting of a NEPS in a less-than-300 year lifetime altitude is unacceptable, the placement of the reactor in the high-altitude orbit should be examined further for reduction of the quantity of trips by increasing the number of tankers, and increasing the number of free-flyers with reactors, electrolyzers, and refrigerators. Other possibilities leading to a more acceptable profile are larger tankers and transporting the water (for fuel production) to orbit on a space-as-available basis.

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* This agrees closely with Boeing's numbers of 31.5 and 31.1 metric tons in Tables 3-2 and 3-3 respectively, since they do include an OMV, emergency power, and life cycle propulsion.

4. COMMUNICATIONS/AIR TRAFFIC CONTROL

4.1 Geosynchronous Communications Platform

Many new concepts in high data rate communications are being developed that will require a transmitter/repeater located in a geosynchronous Earth orbit (GEO). These concepts include direct broadcast video, closed-circuit teleconferencing, electronic mail transmission, and mobile communications. As these concepts are developed and implemented, the number of satellites in GEO could increase to unmanageable proportions if an individual satellite were dedicated to each communications mission. Nuclear power with its high energy density could enable these highly desireable missions by allowing them to be placed on a single communications platform with a large number of antennas, transponders, and/or signal processing capabilities using common structure, power supply, and attitude control systems, thus eliminating the potential congestion in GEO due to the deployment of numerous single mission satellites. There are many potential advantages to this approach to both mission operators and communication service users for a variety of missions.

Since only a finite number of satellites can be located in GEO over the western hemisphere, only satellites performing missions of relatively high commercial appeal and rapid initial cost recovery would be able to reserve places in GEO; other desireable missions would be unable to locate in GEO. The multi-function communications platform requires only a single position in GEO, eliminating the congestion of dedicating a specific position to each communications mission. This platform is described in Figure 4-1.

With a variety of functions performed on a single platform, ground antennas need only to point to one satellite in order to be linked to several functions. This is especially beneficial to smaller users who are then able to use a single ground antenna to service a variety of communications functions. If these functions were each performed by dedicated satellites in GEO, such users would either need to reposition their antenna each time a different function was addressed, or make use of a dedicated ground antenna for each function.

Figure 4-1

GEO COMMUNICATIONS PLATFORM

- PURPOSE

  MULTI-FUNCTION TRANSMISSION INCLUDING
  DIRECT BROADCAST VIDEO, TELECONFERENCING,
  ELECTRONIC MAIL, AND MOBILE RADIO SUPPORT.

- CONCEPT

  PLATFORM(S) IN GEOSYNCHRONOUS ORBIT.
  HIGH POWER, MULTI-BEAM TRANSMISSION.

- ENABLING TECHNOLOGIES

  MULTI-ELEMENT, LONG-LIFE TRANSMITTERS.
  LARGE MULTI-BEAM ANTENNA.
  ADVANCED DATA HANDLING AND SWITCHING.

- POWER USE

  SIGNAL TRANSMISSION, ORBIT/ATTITUDE CONTROL.
  (100-200 KWE)

- NUCLEAR BENEFITS

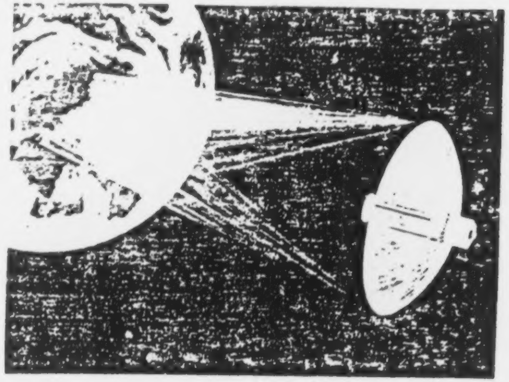
  LESS EXPENSIVE, HIGH POWER FOR TRANSMITTERS.
  AUXILIARY POWER FOR ION STATION KEEPING THRUSTERS.
  UNAFFECTED BY ECLIPSES.

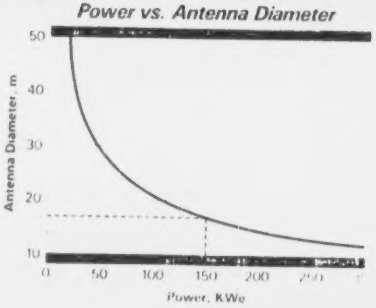
- NUCLEAR CONCERNS

  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

- KEY PERFORMANCE TRADE

  RF OUTPUT POWER vs ANTENNA SIZE.





The combination of several communications missions on a single platform also permits interconnection between the different functions, enhancing system flexibility. Individual transponders are linked in specific combinations for different communications needs. Some signal processing hardware is also shared between users, allowing communications resources to be reassigned in the event of localized failures.

The satellite operators themselves realize a lower operating cost with a multi-function communications platform. Support systems such as power supply, attitude control, thermal management, and structure are provided by the common platform rather than by each communications mission. Using a share of one of these larger-scaled systems not only is of lower cost to the users than their dedicated counterparts, but can be of a higher performance level. A higher power transmitter permits using a smaller antenna at the satellite and/or at the ground station while retaining the same power-aperture product.

A broad variety of communications missions could benefit by colocation on a single geosynchronous platform. These include direct broadcast television, advanced video teleconferencing, and electronic mail transmission.

Direct broadcast television would permit users with consumer-sized (<1m diameter) antennas to receive broadcasts directly from a geosynchronous satellite. This would permit a greater number of channels to be available to viewers, as well as providing uniform program coverage for national broadcasts. These benefits would also extend to viewers in mountainous, rural, and remote areas who presently have limited access to broadcast video.

The Ford Aerospace and Communications Corporation is presently building three DBS satellites for the Direct Broadcast Satellite Corporation, scheduled for launch in 1987. Two of these satellites will together broadcast six high-power channels to the entire continental United States, as well as twelve spot beams of four low-power channels to selected metropolitan areas; the third satellite will be used as an on-orbit spare. The next generation of DBS communications is projected to have 36 high-power and 18 low-power channels, with limited (50% nominal) eclipse capability. The total power required for this mission would be 30 kWe.

Both of these concepts transmit 200 W_{RF}/high-power channel, requiring a receiving antenna of .75m (30") diameter. A reduction in consumer antenna size to .5m (20") diameter would significantly increase the constituency of such a broadcast service, while requiring an increase in transmitted power to 450 W_{RF}/channel. The advanced mission described above would then require 75 kWe of prime spacecraft power. Increases in the number of broadcast channels would proportionally increase the power requirements as shown in Figure 4.2.

Another mission that could profitably locate in an advanced telecommunications platform is a video teleconferencing system. Travel by government and industry for the purpose of attending meetings is a costly enterprise, both in terms of travel expenses and the total time investment in a meeting that may be of only a few hours duration. Much of this cost could be saved by the use of an advanced teleconferencing system that combines video, audio, facsimile, and data communications between parties distant from each other. This kind of service is already being used in limited applications; its appeal indicates a rapid growth rate that will soon saturate and exceed the communications resources available to it. ITT has conservatively estimated that over 300 dedicated satellite transponders may be required by the year 2000 in order to carry the teleconferencing data volume alone.

Electronic mail (via facsimile) transmission is already in place among commercial and government organizations, but may have wide appeal among the consumer sector. Overnight mail delivery is in high demand, even though it is quite costly. Under the many circumstances when an electronically transmitted facsimile would be satisfactory, considerable savings in cost could be realized. Off-net or non-major metropolitan areas would also benefit from this rapid mail delivery. A system concept that would allow for transmission/reception of 10 pages/second from the

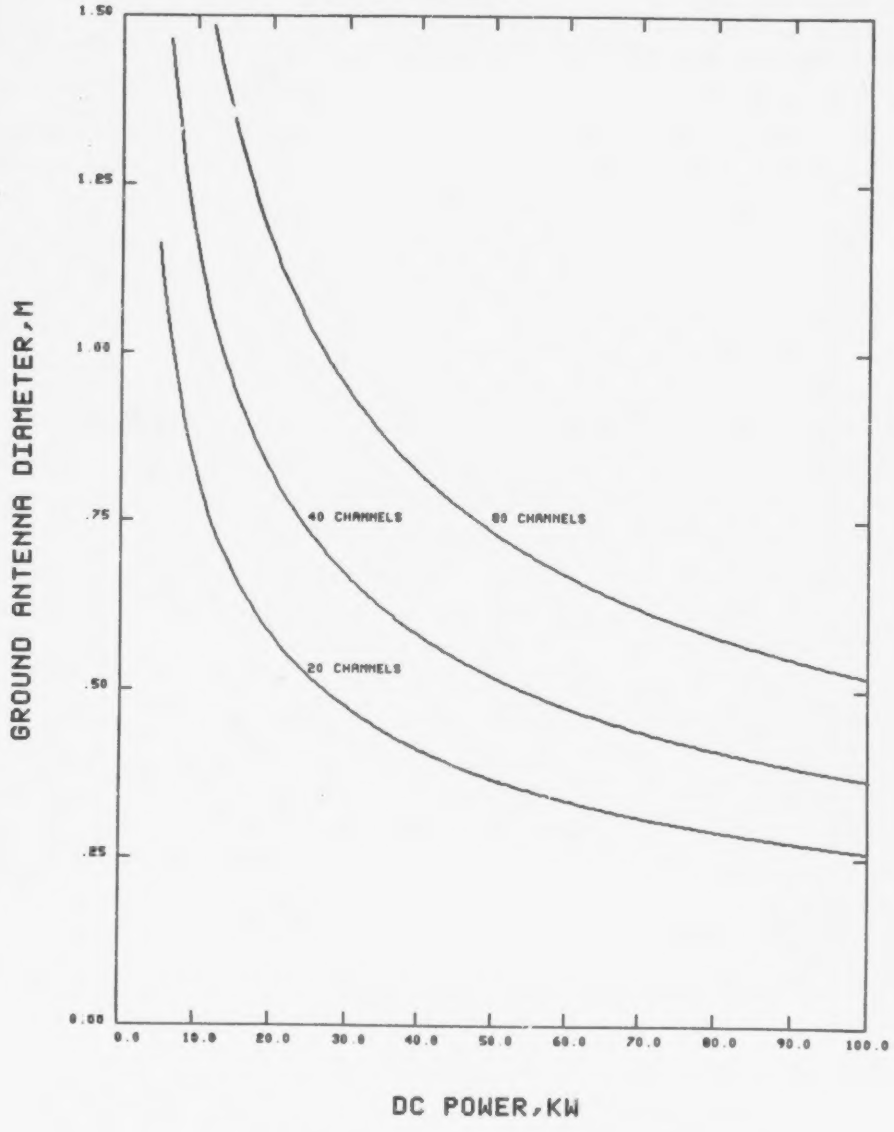


Figure 4-2 COMMUNICATIONS PLATFORM DESIGN TRADEOFF

post offices covering 50% of the U.S. land areas calls for a single satellite requiring 15 kWe of prime power.

The multi-function communications platform thus requires a large quantity of power for sustained operations. Nuclear power enhances the viability of such a platform by providing lower cost power not only for operations, but also for an electric propulsion system for stationkeeping. Electric propulsion could also be used for transfer from low Earth orbit (LEO) to GEO, allowing large structures, such as booms or antennas, to be deployed in LEO, possibly with manned assistance, and then the entire craft transferred by low thrust propulsion to its eventual operating altitude. The nuclear power source is unaffected by Earth eclipse periods, thus permitting optimal longitudinal locations and elimination of the batteries for operation during eclipse periods.

A nuclear power source would produce an enhanced radiation environment to the spacecraft, preventing the use of certain less survivable electronic components. The radiation problem could be addressed by the spot shielding of particularly sensitive parts, as well as the use of a larger separation between the spacecraft and the power supply.

A contract under the auspices of the SP-100 Project with Booz-Allen & Hamilton, Inc. was initiated in July 1984 to study a broad range of civilian/commercial mission applications of space nuclear power; this will provide further clarification of mission applications of space nuclear power. A contract with the COMSAT General Corporation, also through the SP-100 Project, was initiated in July 1984 to specifically study commercial communications mission applications of space nuclear power.

4.2 Air Traffic Control Radar

The Federal Aviation Administration (FAA) does not currently have the capability to maintain positive control of aircraft after they have passed more than 180 nmi from either of the north American coastlines. The capability for FAA, and the International Civil Aviation Organization (ICAO), to maintain positive control of all aircraft over the oceans could be provided with a space-based radar (SBR) surveillance system. Some of the benefits of such a system could include improved safety, fuel efficiencies, timely responses to requested deviations from flight plan due to weather, and reduced departure and arrival delays. The unique characteristics of a space nuclear power source could enable this mission and its many benefits to commercial aviation. This concept is illustrated in Figure 4-3.

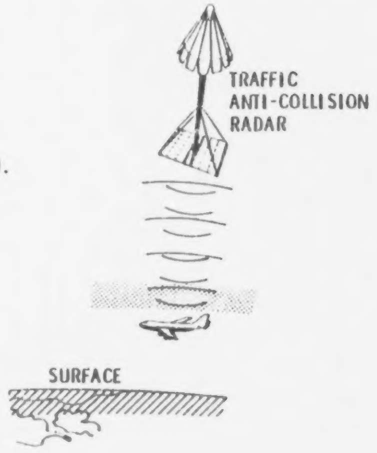
Plans exist to consolidate the present four U.S. controlled Flight Information Regions (FIRs) on the east coast into one, covering about 3.75 million nmi^2 (25-30% of the north Atlantic), and from three into one on the west coast, covering approximately 16.7 million nmi^2 and representing over 75% of the Pacific Ocean above the equator. Those areas outside the FIR's are controlled within specified boundaries by various countries, according to international agreement. None of these uncovered areas are scheduled to be under positive control within the next 20 years, despite projected annual traffic growth of 3-5%. By the year 2000 the air traffic for the north Atlantic will be over 1000 flights every day, all operating without radar coverage. Flights into the Caribbean are already at the saturation point under the current operating constraints. Currently, commercial carriers are experiencing 1/2-1 hour departure delays into this area, and it is estimated that over $7.5 million in fuel was wasted in 1983 because they could not fly at their most efficient altitudes. Much of this waste can be eliminated without compromising safety if the Caribbean area were to be under positive control.

While the Pacific region is larger than the Atlantic, it has a less severe aircraft control problem because air traffic volume is only about 10% of that in the north Atlantic. But since communist countries forbid overflights of their airspace, air routes cannot be moved to take advantage of wind factors. The tracks in the northwest Pacific are confined to narrow corridors, unlike those in the north Atlantic that can be adjusted to take advantage of weather conditions. The recent Korean Airlines tragedy reemphasizes the need to ensure that certain airspace not be violated under any circumstances. With the lack of positive radar position identification, the worst-case uncertainty of aircraft location must

Figure 4-3

AIR/OCEAN TRAFFIC CONTROL

- PURPOSE
  - TRAFFIC PATTERN DETERMINATION AND CONTROL.
  - COLLISION-AVOIDANCE WARNING FOR AIRCRAFT AND/OR SHIPS.
- CONCEPT
  - RADAR PLATFORM(S) IN LEO (700 - 4000 km).
  - NORTH ATLANTIC TRACK COVERAGE.
  - SKIN TRACKING MODE, SMALL TRANSPONDER ON VESSEL.
  - DUAL MODE TRANSMITTER FOR VERTICAL/HORIZONTAL RESOLUTION.
- ENABLING TECHNOLOGIES
  - MULTI-BEAM SCANNING ANTENNA.
  - HIGH POWER TRANSCEIVER MODULES.
- POWER USE
  - RADAR PULSE TRANSMISSION.
  - (40-200 KWE)
- NUCLEAR BENEFITS
  - HIGH POWER ALLOWS SMALLER ANTENNA,
  - MORE COVERAGE, HIGHER RESOLUTION.
  - ELECTRIC PROPULSION FOR ORBIT/ATTITUDE CONTROL.
- NUCLEAR CONCERNS
  - ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.
- KEY PERFORMANCE TRADE
  - POWER LEVEL vs ANTENNA SIZE.



be added to the safe separation distance in order to maintain absolute separation between aircraft in neighboring corridors.

The FAA and ICAO envision upgrading oceanic air traffic control in two stages. The first stage is an Oceanic Display and Planning System (ODAPS). This is a computer simulation of individual aircraft tracks, in non-radar environments, based on their track histories while under positive control. In addition to providing an automated traffic conflict probe, ODAPS allows assigning more fuel-efficient routes and altitudes without reducing aircraft separation standards (currently 60 or 90 nmi horizontal separation). The concept, already demonstrated in the Caribbean, is scheduled for implementation within the next 2-4 years in the north Atlantic, the Caribbean, and the Pacific. This system does have limitations: updates of an aircraft's position are only given at 40-60 minute intervals and transmissions, and receptions are only as good as the aircraft's navigation equipment. In addition, variations in track and airspeed due to winds make the system less accurate than desired.

The second system for upgrading control is an Automatic Dependent Surveillance (ADS). This would report position information derived from on-board navigation equipment. While this offers a significant improvement over ODAPS, it still would not provide the degree of positive control required because of inherent inaccuracies in the method of position determination. Truly positive control can only be obtained through independent (off-board) verification of an aircraft's position. The minimum amount of information required for positive control is aircraft position, identification, and altitude.

These planned enhancements will improve the FAA's and ICAO's oceanic control system in the near future, but still will not provide the precise information required to reduce aircraft spacing while retaining the necessary degree of safety. If positive control were available, aircraft spacing could be reduced by 75% or more, and timely warnings could greatly reduce the likelihood of mid-air collisions. In addition, response times to requests for aircraft flight path deviations due to weather could be appreciably reduced from the current average of about 20 minutes. Departure delays could also be significantly reduced.

Preliminary analysis of a space-based radar system for aircraft traffic control yields a power requirement in the range of 50 to 200 kWe, depending on such factors as mission characterization, resolution, orbit altitude, number of targets, range of coverage, and antenna size. Desired resolution for locating and tracking commercial aircraft in the north Atlantic corridor is 75 meters vertically by 500 meters horizontally. A very large antenna would be required for tracking from geosynchronous orbit altitude, even when high power is available for signal transmission. Low orbit operation is impractical because of the number of radar platforms that would be needed for continuous coverage of the target zones. A possible compromise is the use of a mid-altitude orbit, both reducing the number of spacecraft required while not requiring large antennae. This has the liability of a high natural radiation environment that would seriously degrade the performance of solar arrays should they be used as a power source. Nuclear power offers a significant benefit in this regard since operation in the radiation belts is possible without power degradation. Additional benefits are that high power availability permits smaller antenna size, broader coverage, higher resolution, and more on-board processing capability. The compactness of the nuclear power system also simplifies spacecraft attitude control. Finally, the combination of the nuclear power source with an electric propulsion system might further enhance the mission by offering efficient orbit delivery from LEO and long-term propellant utilization for orbital maintenance and attitude control.

A nuclear power source would produce an enhanced radiation environment to the spacecraft, preventing the use of certain less survivable electronic components. The radiation problem could be addressed by the spot shielding of particularly sensitive parts, as well as the use of a larger separation between the spacecraft and the power supply.

This commercial air traffic control mission could be integrated with other missions serving the public or private sectors, thereby reducing the total number of spacecraft required. General purpose observational spacecraft could provide data to a variety of users at lower cost than would be required with dedicated constellations.

A contract through the SP-100 Project with the General Electric Corporation to study the aforementioned FAA oceanic surveillance mission was initiated in July 1984 and will shortly provide amplification and clarification of this mission.

4.3 Conclusions and Recommendations

Conclusions

- Advanced civil communications and Earth observation missions will require power levels commensurate with those provided by space reactor power systems.
- The advantages of space nuclear power in the areas of lower mass, solar independence, and high survivability can enhance missions performance.

Recommendations

- Further analyses of advanced Earth observation/service missions should consider the incorporation of a space reactor power system. The mission planning activity should take advantage of the performance benefits available from nuclear power.
- The continuing definition and development activities associated with space reactor power system technology should coordinate with the mission studies to ensure compatibility with eventual mission requirements on the power system.

5. PLANETARY EXPLORATION

5.1 Introduction

Although there have been missions to Mars, Venus, Jupiter and Saturn, the far outer planets, (Uranus, Pluto, Neptune) and the small bodies, (comets and asteroids), have not been visited. It is due, in part, to the difficulty in reaching these targets that has prevented them from being visited by a spacecraft to date. However, a nuclear electric propulsion (NEP) spacecraft (Figure 5-1) has the performance potential of opening up these heretofore unvisited targets to detailed scientific exploration (Ref. 5-1). The following five items from Ref. 5-2 are the major science objectives for outer planet exploration:

1. For the primary body, determine its internal structure, surface and atmosphere;
2. For the satellites, determine internal structure, surface, and any atmosphere;
3. Explore ring structures that might exist about the primary;
4. Determine the magnetic field of the primary, the magnetosphere of the system and the magnetospheric interactions between trapped radiation and the primary and its satellite;
5. Explore the interplanetary environment that exists beyond the orbit of Saturn.

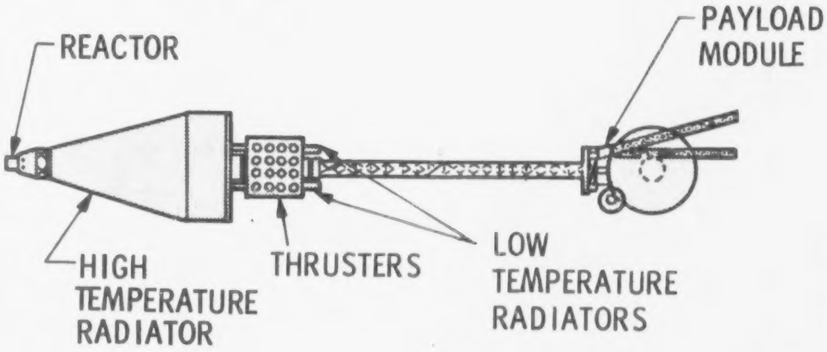
The small bodies, i.e. asteroids and comets, are currently of great interest in planetary exploration because they have not been visited and may contain matter unchanged since the creation of the Solar System. A single asteroid rendezvous and sample return mission would greatly contribute to the understanding of these bodies. The primary objectives for the initial investigations of asteroids are to determine (for several asteroids carefully selected on the basis of diversity) their:

1. Composition and physical state;
2. Surface morphologies (and to gather evidence for endogenic and exogenic processes and evidence bearing on the character of precursor parent bodies);
3. Internal properties including states of magnetization.

Figure 5-1

JPL

NUCLEAR ELECTRIC PROPULSION (NEP) SPACECRAFT


REACTOR
PAYLOAD MODULE
HIGH TEMPERATURE RADIATOR
THRUSTERS
LOW TEMPERATURE RADIATORS

FEATURES

- SIDE THRUST
- 100 kW REACTOR POWER SYSTEM
- SPACECRAFT INTEGRATED ALONG THERMAL GRADIENT
- NO THRUSTER IMPINGEMENT
- CLEAR FIELD OF VIEW FOR SCIENCE
- LOW TEMPERATURE RADIATORS PARALLEL TO SUN LINE

Like asteroids, comets are thought to contain evidence of early Solar System processes. This evidence as well as the potentially important opportunity to investigate cosmic plasma-physics processes have led to the following science objectives for comet exploration (Ref. 5-3):

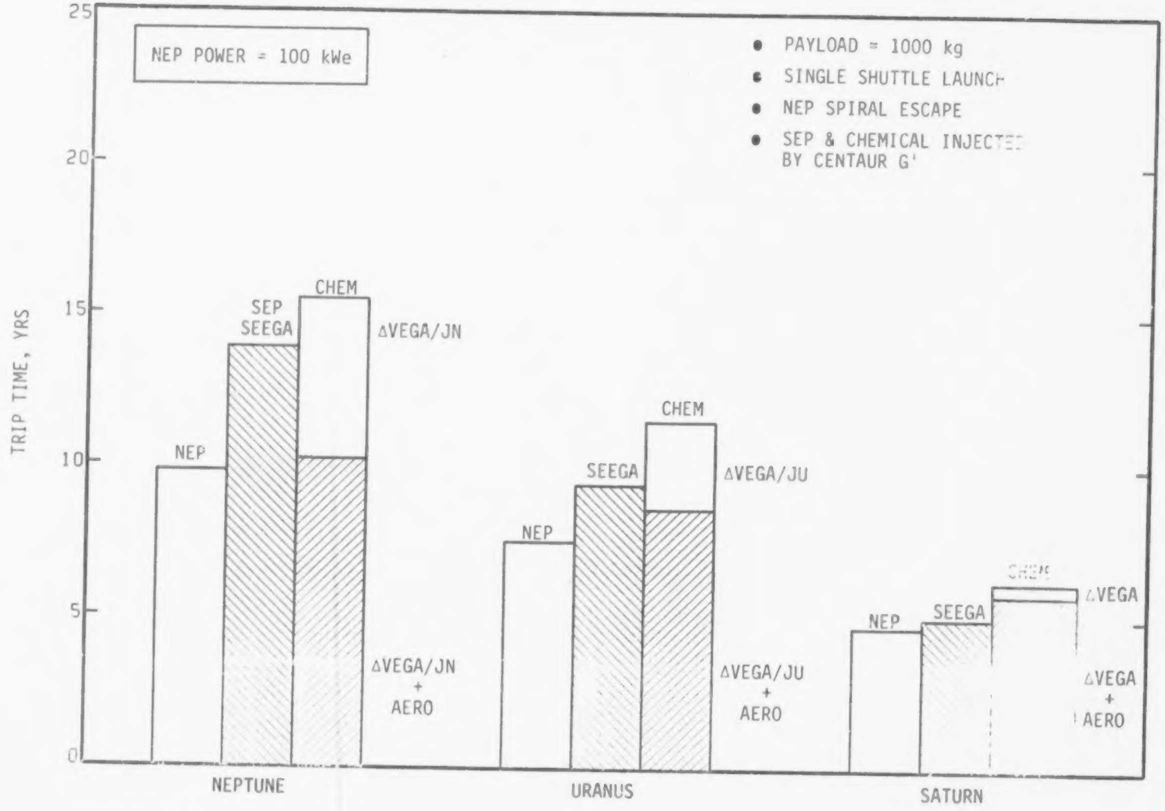
1. Determine the composition and physical state of the nucleus (and the ejected gas and dust);
2. Determine the processes that govern the composition and structure of cometary atmospheres;
3. Investigate the comet's interaction with the solar wind.

It has also been recommended that cometary investigations be carried out over a sufficiently large fraction of a comet's traverse through the inner Solar System, and ultimately over a sufficiently diverse population, to allow investigation of a comet's evolution during its active life.

The previous paragraphs discussed why we want to explore the outer planets and the small bodies. The following will explain the performance advantages of a nuclear power supply, i.e. NEP, to carry out these explorations. Besides NEP, one could use chemical propulsion or solar electric propulsion (SEP) as the transportation system for outer planet orbiters or small body sample return missions. Large amounts of energy are required to reach the outer planets in a reasonable time period. NEP can provide this energy and still meet the other mission requirements, i.e. payload, single Shuttle launch, etc. Figure 5-2 presents a comparison of trip times for outer planet orbiters under the constraints of a fixed payload and a single Shuttle launch. It is clear that NEP is superior. Even SEP is better than the all-chemical propulsion options. In Figure 5-2, the top of the chemical propulsion bars indicate the trip time using both Earth and Jupiter gravity assists. For Neptune and Uranus, the chemical propulsion performance has been augmented by aerocapture at the planet, but even so, NEP is superior. For this comparison, the mission initial mass has been limited to one Shuttle payload. Figure 5-3 removes this constraint but selects a 10 year trip time for an example Neptune orbiter mission (Ref. 5-4). Figure 5-3 presents a comparison of NEP to alternative (some very advanced) propulsion options. The basis of comparison

Figure 5-2

OUTER PLANET ORBITER MISSION TRIP TIMES



is the initial mass in low Earth orbit (LEO). NEP is again clearly superior.

A recent study by Science Applications International Corp. (Ref. 5-5) determined the performance of NEP, SEP and chemical propulsion for sample return missions to three comets: Encke, Tempel 2, and Wild 2. The results of this study are presented in Table 5-1. The flight modes are: 1) ballistic (chemical propulsion) using two Shuttle launches and the on-orbit-assembly of two Centaur G prime upper stages and either an Earth gravity assist trajectory (ΔVEGA) or a direct trajectory; 2) SEP using a single Shuttle launch, and a Centaur G prime upper stage; and 3) NEP using a single Shuttle launch without an upper stage but with a long (about 1 year) spiral escape from Earth, or with a fully fueled G prime upper stage and no spiral escape. The basis for comparison was both flight time and mass margin for a given payload. The mass margin is the difference between the propulsion system capability and the mission injected mass requirement. A negative mass margin indicates that the mission is not possible. Table 5-1 again implies performance superiority of NEP to chemical propulsion. For these comet sample return missions both SEP and NEP have advantages. Although not clearly superior compared to SEP for these missions, Table 5-1 does demonstrate the capability of NEP for comet sample return missions.

The preceding paragraphs have demonstrated the performance enhancing characteristics of a nuclear electric propulsion spacecraft for planetary exploration. Nuclear electric propulsion provides exciting benefits for planetary exploration. With these benefits certain issues will need to be addressed. One of the more important issues is the question of the compatibility between the radiation produced by a nuclear power supply and the sensitive scientific instruments carried on planetary spacecraft.

The total radiation dose from a candidate 100 kWe nuclear power supply has been specified as 5×10^5 rad gamma (Si) and 1×10^{13} neutrons/cm^2 at 25 meters after 7 years. Instruments that will be sensitive to this radiation include gamma ray spectrometers, energetic particle detectors and any instrument using the visible or ultraviolet spectrum. Instruments

Figure 5-3

JPL

MISSION INITIAL MASS VS PROPULSION SYSTEM
NEPTUNE ORBITER

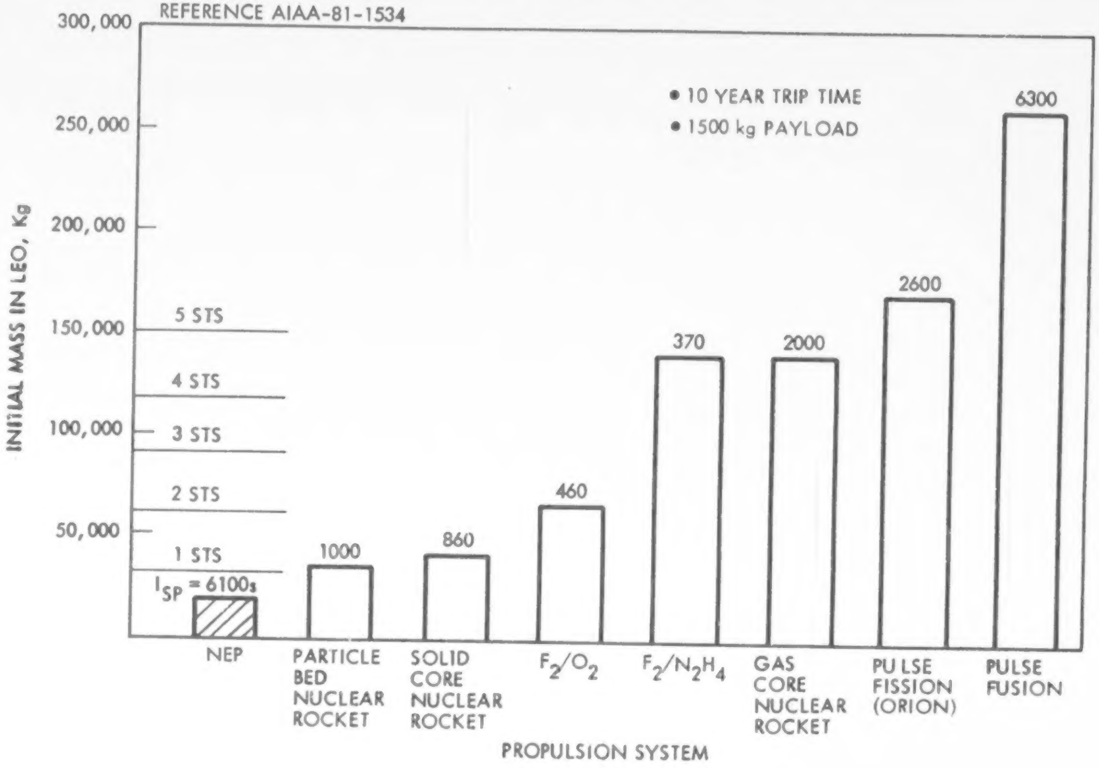


Table 5-1

SUMMARY OF COMET SAMPLE RETURN FLIGHT MODE OPTIONS

FLIGHT MODE		ENCKE		TEMPEL 2		WILD 2	
		MASS MARGIN (KG)	FLIGHT TIME (YRS)	MASS MARGIN (KG)	FLIGHT TIME (YRS)	MASS MARGIN (KG)	FLIGHT TIME (YRS)
BALLISTIC	o △ VEGA	-10000	10.1	4000	11.1	--	--
STS + G' + G'	o DIRECT	-13000	8.1	-1200	9.1	250	8.9
SEP + G'		900	6.1	800	4.9	2700	6.0
NEP	o SPIRAL ESCAPE	5000	6.9	7500	6.8	7200	7.0
	o WITHOUT SPIRAL	2500	5.7	4500	5.5	4500	5.8

- 100 kWe, 4370 kg Dry Mass NEP
- 38 kWe, 1741 kg Dry Mass SEP

(SAI Data)

that measure magnetic fields or plasma particles and radio science instruments are thought to be relatively insensitive to this radiation. Beyond the question of instrument sensitivity is the issue of total dose or damage to the electronic components within the science payload. The maximum expected radiation dose to the electronic components within the latest, state-of-the-art planetary spacecraft (Galileo), is 7.5×10^4 rad and 2.5×10^{10} neutrons/cm^2. The environment in which the Galileo spacecraft must operate is dominated by the natural electrons and protons of the Jupiter environment. The electronic components have the capability to survive environments that are a factor of two larger than that expected. Also, a new generation of hardened electronics is expected to be developed by the time SP-100 is in operational space use. There are at least three approaches through which the radiation issue may be handled: 1) more shielding at the power supply; 2) spot shielding at the payload, or 3) a large separation distance between the nuclear power supply and the payload. The estimated required separation distance between the power supply whose radiation environment was specified above and the Galileo payload rated at 7.5×10^4 rad is 65 m. Figure 5-4 presents this relationship.

A recent study by JPL (Ref. 5-6) suggested that by using different components the radiation environment for planetary spacecraft could be raised to 2.5×10^5 rad. Also, mercury is a good gamma-ray shield and a NEP spacecraft using mercury ion thrusters will carry several thousands of kilograms of mercury which would be configured so as to act as a gamma-ray shield. The investigation into the compatibility between nuclear radiation and planetary instruments and missions is continuing at JPL under the auspices of the SP-100 Project.

The next four sections present in detail descriptive examples of planetary missions that would be significantly enhanced or enabled by a nuclear power supply.

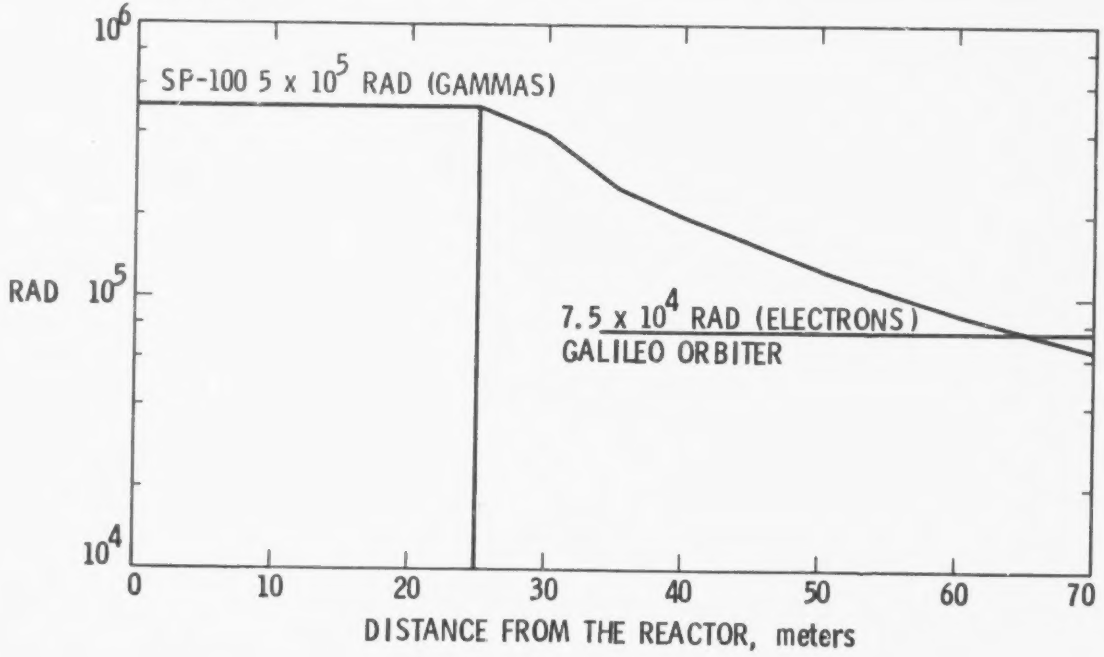
5.2 Multi-Asteroid Sample Return

The asteroids comprise a numerous and diverse population of small bodies in the solar system, distributed mainly in the spatial region

Figure 5-4

PLANETARY SPACECRAFT RADIATION DOSE REQUIREMENTS

- NOTE: Hg PROPELLANT MAY BE ABLE TO BE CONFIGURED TO ACT AS A GAMMA SHIELD



between Mars and Jupiter. Scientific interest in asteroids is heightened by the expectation that these relatively primitive bodies hold important clues to the physical and chemical processes associated with the early development and evolution of the solar system. First generation missions are being planned as a component of the SSEC*-recommended Core Program for planetary exploration. Such missions will provide rendezvous/orbiter science capability for several selected asteroid targets in the main belt and in near-Earth space. Depending on data return from this asteroid exploration initiative, and on the availability of advanced propulsion systems, there could be considerable interest in returning samples from one or, preferably, several asteroids. The information obtained in Earth-based laboratories would be of scientific value in itself, but may also support future programs in extraterrestrial resource utilization.

The science value of sample return may be greatest if the material is not previously known as a meteorite type. Carbonaceous chondrites, which are the most primitive, most studied type of meteorite, are very rare in meteorite collections, presumably because of their fragility and destruction during atmospheric entry. A sample return mission should include a C-type asteroid target, preferably one on which bound water has been detected. Some issues which can only be resolved by the study of returned samples of carbonaceous chondrites include: water content, state of hydration, indigenous organic compounds, and improved knowledge of solar system abundance values for certain chemical elements. Other types of studies that are best carried out on samples rather than being made in situ include: mineralogy and petrography, shock and irradiation effects, age dating, stable isotope measurements, identification of organic chemicals, and radiactivity.

A minimum mass of several kilograms seems to be adequate for each target sampled. Of greater concern is to assure that the sample is representative of the object being sampled. This could be accomplished if the orbiting spacecraft and the lander include a complement of science experiments in addition to the sample collecting systems. Minimal information about the sample's environment can be gathered by imaging, global chemistry characterization provided by X-ray and gamma-ray spectroscopy, global geophysics including density and gravity field data, and in situ surface chemistry provided by alpha backscatter and X-ray fluorescense. It may also be desired to sample several sites on the same target.

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* Solar System Exploration Committee of the NASA Advisory Council.

In the proposed mission concept (see Figure 5-5), the space vehicle system would rendezvous with several (nominally 3) asteroids in succession, staying at least 2 months at each target while performing global science coverage, site selection and characterization, and sample collection operations. A separable, reuseable lander/ascent/rendezvous vehicle collects and returns the samples to the low-thrust transport orbiting the asteroid. Both solar electric (SEP) and nuclear electric propulsion (NEP) would enable this mission - the ballistic flight mode using chemical propulsion is not practical since the velocity impulse requirement exceeds 10 km/sec. With low-thrust propulsion, flight times along each of the trajectory segments between asteroid targets lie in the range of 600 to 800 days. The SEP system design requires a 60 kWe solar array with 4:1 array concentration. A NEP transport with power rating of 100 to 150 kWe offers better performance in terms of larger payload mass, shorter trip time, and/or greater flexibility in target selection. A typical mission shown in Figure 5-5 could return samples from three asteroids with a round trip time of about 8 years or from four asteroids in 10 years.

5.3 Comet Nucleus Sample Return

The primary objective of this mission is to collect a sample of undisturbed comet material from beneath the surface of an active comet, and return it to the Earth in a minimally altered state. Secondary objectives are to characterize the comet to a level consistent with a rendezvous mission and, as an option, monitor comet dynamics through perihelion and aphelion with a long-lived lander/station. The comet nucleus sample return mission has been recommended as an augmentation to the SSEC Core Program for planetary exploration.

Figure 5-5

MULTI-ASTEROID SAMPLE RETURN

- **PURPOSE**

  RETURN SURFACE SAMPLES FROM SEVERAL ASTEROIDS.
  SUPPORTING SCIENCE BY ORBITER/LANDER.
  EVALUATE RESOURCE UTILIZATION POTENTIAL.

- **CONCEPT**

  RENDEZVOUS WITH 3 OR 4 ASTEROIDS.
  60-DAY STAY AT EACH TARGET.
  SAMPLE ACQUISITION BY REUSEABLE LANDER.

- **ENABLING TECHNOLOGIES**

  ELECTRIC PROPULSION (SEP, NEP).
  AUTOMATED RENDEZVOUS/DOCKING.

- **POWER USE**

  SEP - 60 KWE ARRAY W/CONCENTRATORS.
  NEP - 100 KWE.

- **NUCLEAR BENEFITS**

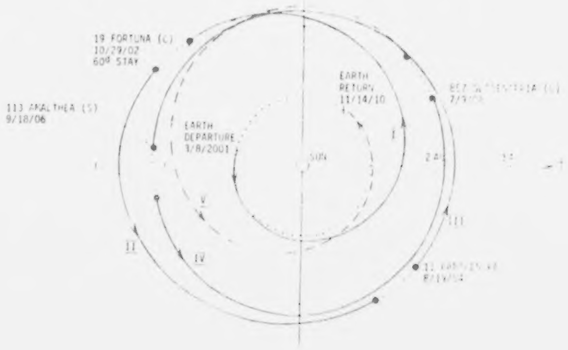
  LARGER PAYLOAD MARGIN.
  SHORTER TRIP TIME.
  TARGET SELECTION FLEXIBILITY.

- **NUCLEAR CONCERNS**

  RADIATION AND THERMAL SHIELDING OF PAYLOAD.

- **KEY PERFORMANCE TRADE**

  NUMBER OF TARGETS/TRIP TIME vs POWER LEVEL.


19 FORTUNA (C)
10/29/02
60d STAY
113 AMALTHEA (S)
9/18/06
EARTH DEPARTURE
3/8/2001
EARTH RETURN
11/14/10
SUN
2 AU
I
II
III
IV
V

ASTEROID MULTIPLE SAMPLE RETURN PROFILE – ION DRIVE [illegible]

The proposed mission consists of several elements. The spacecraft bus would carry a science payload to perform the nucleus characterization and site documentation objectives, and would provide relay control and communication during the sampling process. Two sample devices are specified to collect two 1-meter cores of the nucleus. These are to be separately deployed from the spacecraft and recovered through an automated rendezvous and docking procedure (see Figure 5-6). The second sampler would carry with it a long-lived lander that would be anchored to the comet's surface upon impact. The lander would be capable of monitoring nucleus surface activity over one orbital period of the comet or at least through perihelion and aphelion passages. After recovery by the spacecraft, the core samples would be hermetically sealed in an environmentally controlled capsule to prevent thermal, chemical or radiation contamination during the return trip to Earth. The samples would be returned to a circular, Shuttle-compatible orbit to insure the probability of quick recovery. A space station can play an important role in recovery operations and initial testing of the sample capsule contents.

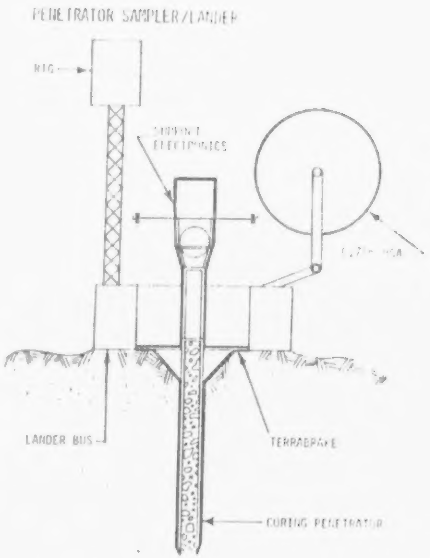
Potential targets for the comet nucleus sample return mission include all the short-period comets being considered for an earlier rendezvous mission. Emphasis has been placed, however, on the comets Encke, Tempel 2 and Wild 2. These three comets, in addition to satisfying the established criteria of good rendezvous targets, have perihelion passages occurring shortly after the turn of the century thus providing opportunities for launch prior to the year 2000 but still allowing time for data to be returned from a possible precursor rendezvous mission. Depending upon the propulsion system and flight mode selected, launch opportunities for near-perihelion encounters with at least one of these comets exist every year from 1997 to 2002.

Potential flight modes for mass delivery include ballistic/chemical propulsion, solar electric propulsion (SEP), and nuclear electric propulsion (NEP). Ballistic opportunities are more limited in comet selection, have long round-trip times, and generally require several advanced technologies including on-orbit assembly of Centaur stages and space storable retropropulsion. SEP is an enabling technology for all comet sample

Figure 5-6

COMET NUCLEUS SAMPLE RETURN

- PURPOSE
  - OBTAIN PRISTINE SAMPLE OF COMET NUCLEUS.
  - MONITOR COMET DYNAMICS VIA LONG-LIVED LANDER.
- CONCEPT
  - RENDEZVOUS WITH SHORT-PERIOD COMET.
  - CONDUCT SITE SURVEILLANCE/DOCUMENTATION.
  - COLLECT 1-METER CORE SAMPLES FROM 2 SITES.
  - LEAVE MONITORING STATION ON SURFACE.
- ENABLING TECHNOLOGIES
  - ELECTRIC PROPULSION (SEP,NEP)
  - AUTOMATED RENDEZVOUS/DOCKING.
- POWER USE
  - SEP-36 KWE ARRAY W/CONCENTRATORS.
  - NEP - 100 KWE.
- NUCLEAR BENEFITS
  - EARLY ENCOUNTER-REDUCED DUST HAZARD.
  - LARGE PAYLOAD MARGIN.
  - SHORTER TRIP TIME.
- NUCLEAR CONCERNS
  - RADIATION AND THERMAL SHIELDING OF PAYLOAD
- KEY PERFORMANCE TRADE
  - TARGET COMET SELECTION.
  - SEP vs NEP FLIGHT MODE.


PENETRATOR SAMPLER/LANDER
RIG
SUPPORT ELECTRONICS
LANDER BUS
TERRABRAKE
CORING PENETRATOR

return missions providing that comet rendezvous occurs in the vicinity of perihelion; round-trip times are 5 to 6 years and a single Shuttle/Centaur launch is sufficient. The availability of NEP transportation enhances the mission opportunities through its higher payload performance. NEP permits greater mission design flexibility by providing a wider range of encounter time thus reducing hazards due to comet dust activity near perihelion. Shorter trip times may also be possible. The large amount of electric power available from the nuclear reactor source is not absolutely necessary for the science experiments and sampling process, but could be viewed as an enhancing option.

5.4 Saturn Ring Rendezvous/Exploration

Important science questions have been raised by the spectacular observations of Saturn's rings by the Voyager spacecraft. The origin and evolution of the rings as relating to processes at work in the Saturn/satellite system is of great interest. A follow-on Saturn orbiter mission with capabilities similar to Galileo will provide long duration, remote observations which should yield a better characterization of ring structures, dynamics and possible satellite interaction. However, many questions dealing with origin and processes of ring formation and the nature of ring particles will likely remain unresolved until it is possible to perform close-up (in situ) experiments.

The primary objective of this advanced mission to rendezvous with Saturn's rings is to conduct detailed observations of individual ring particles and in situ composition measurements of the particles and their immediate environment. This will require spacecraft systems with enormous propulsive capability. Chemical propulsion systems are not adequate to attain near-circular orbits even at the outer edge of the ring system. This mission requires a high performance low-thrust system which, at Saturn's distance from the Sun, is enabled only by a nuclear power source. Given the large mass delivery potential of nuclear electric propulsion, it becomes reasonable to consider other important science objectives which can be achieved enroute to ring rendezvous. These secondary objectives comprise an extended exploration of the Saturn system and might include such options as atmospheric entry probes, a Titan orbiter, Titan buoyant station and/or lander, close investigation of the other satellites, global studies of Saturn's atmosphere, and a spatial/temporal investigation of the system of fields and particles.

This mission concept employs a nuclear-powered electric propulsion system that transports the payload from Earth to Saturn in about eight years. Upon reaching the vicinity of Saturn, the vehicle then spirals inward along continuously decreasing circular orbits in the equatorial plane. The orbit of Titan is reached in about 100 days. Depending on possible mass dropoff at Titan, an additional 1.5 to 2 years is required to spiral in to a circular orbit at the distance of the inner D ring (1.1 Saturn radii). When the vicinity of the outer G ring is reached, the thrusting profile is modified to keep the spacecraft in a non-Keplerian minor-circle orbit just above or below the ring plane. The spacecraft thus skims across the rings toward Saturn, like the stylus of a phonograph gliding across a record, making detailed observations of each ringlet from a very close distance. At intervals during this orbital process, thrust could be terminated for a few hours causing vertical motion toward the rings or through low density gaps. Alternatively, a tethered science package might be lowered into the ring plane for in situ measurements.

Performance of this mission as shown in Figure 5-7 requires an electric power from the reactor/power conversion system in the range 100-150 kWe. This assumes a 1500 kg mission module, a power/propulsion system dry mass in the range 5000-6000 kg, and a maximum mission duration of 10 years. To illustrate the mission time vs. power tradeoff, at 5000 kg dry mass the mission time is reduced from 10 years to 7 years as power increases from 100 to 150 kWe. At 6000 kg dry mass, the 10-year maximum requires a power level of 120 kWe whereas a 150 kWe system could accomplish the mission in 8 years.

5.5 Far Outer Planets Orbiter/Probes

The Solar System Exploration Committee (SSEC)-recommended Core Program for planetary exploration includes a Uranus flyby/probe mission to continue the reconnaissance of Uranus beyond Voyager. Neptune and Pluto are also considered high priority targets, but missions were thought to be

Figure 5-7

SATURN RING RENDEZVOUS/EXPLORATION

- PURPOSE

  DETAILED INVESTIGATION OF RING STRUCTURE/COMPOSITION.
  EXTENDED OBSERVATION OF SATURN AND TITAN.

- CONCEPT

  SPIRAL IN PAST TITAN-PAYLOAD DROPOFF.
  CONTINUE SPIRAL TO INNER D-RING.
  MAINTAIN 1-20 km DISTANCE ABOVE RING PLANE.

- ENABLING TECHNOLOGIES

  ELECTRICAL PROPULSION.

- POWER USE

  PROPULSION (100-200 KWE).

- NUCLEAR BENEFITS

  ENABLES MISSION (NO NEAR-TERM ALTERNATIVE).
  LARGE PAYLOAD CAPABILITY.

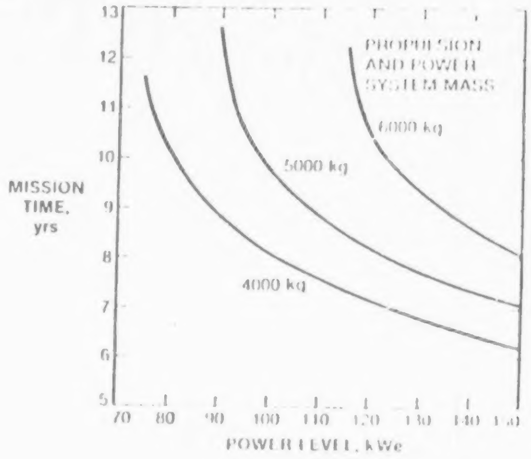
- NUCLEAR CONCERNS

  POSSIBLE INTERFERENCE WITH SCIENCE MEASUREMENTS.
  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

- KEY PERFORMANCE TRADE

  TRIP TIME/PAYLOAD vs POWER LEVEL.

- SP-100 NUCLEAR POWER SOURCE
- 1500 kg (P/L AND SCIENCE) PAYLOAD
- 2 yr SPIRAL FROM TITAN ORBIT TO [illegible]



impractical during this century due to scheduling and technology limitations. However, as a potential augmentation option, an integrated and comprehensive program of scientific exploration of the far outer planets with orbiters and atmospheric probes can be enabled by advanced propulsion technology such as nuclear electric propulsion. The program is comprised of three individual missions: Uranus orbiter/probe, Nepturn orbiter/probe, and Pluto orbiter. Short flight time to these targets is a key aspect here - it is desired that no mission exceed 12 years duration.

Scientific objectives for exploration of these planets may be categorized in six areas of investigation: 1) atmospheres, 2) interiors, 3) surfaces of Pluto and satellites, 4) ring system, 5) magnetospheres, and 6) solar wind interaction. Uranus and Neptune have deep, hydrogen-dominated atmospheres. A successful Voyager 2 extended mission will give the rotation rate and axis and preliminary atmospheric properties above the clouds (i.e., structure, circulation patterns, wind speeds and composition) at a single point in time. The advanced exploration missions can improve our knowledge of the above by extending the interval of measurements using synoptic coverage. This also provides information about the dynamic behavior of the atmosphere including seasonal changes. Better data are obtained because the orbiter is able to work in an adaptive mode; that is, modifying its data acquisition patterns in response to prior discoveries. A very important objective for an exploration program is to measure the atmospheric properties above, in and below the cloud layer. The H/He ratio is of particular interest. The objective is satisfied in part with an atmospheric probe that is also able to provide "ground-truth" data above the clouds for calibrating the orbiter's remote sensing instruments.

The mass, higher order gravity field coefficients, radius, shape and excess thermal emission are essential data for modeling the interiors of planetary bodies. Among the goals of the proposed orbiter missions should be long-term observations of the planets and encounter of as many satellites as possible at close range where accurate photometric and radiometric tracking data can be acquired. This data can be used to derive the bulk density for a body and to infer its composition and internal structure. For Pluto and its large satellite Charon, and the satellites of Uranus and Neptune, the surfaces reveal important clues regarding the origin and evolution of these bodies. An important orbiter mission objective is to characterize the surface properties, i.e., morphology, composition, and physical state. Finally, the extended observation time and spatial coverage provided by a Uranus and Neptune orbiter would greatly enhance the science potential of particle and field experiments relevant to magnetosphere and ring investigations.

In the example design concept, initial elliptical orbits would be established at Uranus and Neptune for purposes of science observations over a large range of distances from the planet. The atmospheric entry probe could be released from orbit, or alternatively, on approach to the planet. In the case of Neptune, the initial orbit would allow close encounter with Triton which is massive enough to assist in orbit capture and provide significant orbit change through repeated gravity-assist encounters. At Pluto, a circular orbit at about ten planet radii would place the spacecraft into near-rendezvous conditions with its satellite Charon. Subsequent maneuvering, made easy by Pluto's small gravitational field, would allow close-range investigation of both bodies and the spatial regions between them.

There are only two advanced technologies that can enable this far outer planet exploration program within a 12-year trip time constraint -- aerocapture and nuclear electric propulsion (NEP). Aerocapture can be employed only at Uranus and Neptune. Ballistic flights with aerocapture need to be combined with on-orbit assembly of injection stages (e.g. two stacked Centaurs), and also with Jupiter swingby in the case of Neptune. In contrast, a NEP system with commonality in design enables all three missions. Spiral escape from low Earth orbit can be employed in lieu of Centaur stages thereby requiring only a single Shuttle launch. Launch can occur any year since the infrequent Jupiter swingby opportunities are not required for performance advantage. Furthermore, NEP has greater flexibility as to orbit spatial orientation and, therefore, probe entry/descent conditions, and orbiter science operations are potentially more flexible because of NEP's greater capability for orbit change maneuvers compared to chemical retropropulsion. Figure 5-8 describes the key performance trades. With a 100 kWe NEP system, flight times from low Earth orbit to initial planet capture orbit are about 8 years for Uranus and 10 to 12 years for Neptune or Pluto missions. A one to two year reduction in flight time is possible by increasing the power level to 150 kWe or, alternatively, by eliminating the Earth escape spiral and injecting the NEP vehicle beyond escape energy by on-orbit assembled Centaur stages (a single Centaur fully fueled effects a one-year flight time reduction to Neptune while two Centaur stages allow a 2.5 year reduction). Figure 5-9 clearly shows the effect of higher power, up to 500 kWe, on reduction in flight time.

5.6 Mission Applications Summary

The foregoing discussion introduced the concept of a nuclear electric propulsion spacecraft and has demonstrated the performance characteristics of this type of spacecraft for planetary missions. The radiation compatibility issue between the nuclear power supply and the science instruments was discussed. Four types of planetary missions that would be enhanced or enabled by a nuclear power supply were described in detail. Other missions than just these four would be significantly enhanced or enabled by a nuclear power supply. Table 5-2 presents the characteristics of 8 nuclear electric propulsion planetary missions. In conclusion, there are many potential planetary missions that would greatly benefit from a nuclear power supply. Several of these missions are relatively well defined and a study of planetary missions is continuing at JPL under the sponsorship of the SP-100 Program. The committment to the development of a nuclear power supply could make these missions a reality and would encourage NASA to seriously plan for nuclear electric propulsion missions and move on to a new era of space exploration.

5.7 Conclusions and Recommendations

Conclusions

- Electric propulsion powered by a nuclear electric power system can enhance a class of planetary exploration missions that NASA is now starting to plan. Some very ambitious missions are enabled by this technology.

- While other advanced transportation techniques (aerobraking, on orbit assembly of multiple chemical stages, etc.) can apply to some advanced planetary missions, electric propulsion powered by a nulcear electric power system has a much wider applicability.

- A nuclear power supply characterized by a specific mass of 30 kg/kWe, and end-of-life power of 100 kWe and a full power life of 7 years would be highly effective in supporting the missions alluded to above.

Recommendations

- The planning of future planetary missions should include the capability provided by nuclear electric propulsion.

- The ongoing and future planning and development activities for a nuclear electric power system should include the requirements of nuclear electric propulsion planetary missions.

- Nuclear electric power systems with specific masses lower than 30 kg/kWe should be pursued.

- Nuclear electric power systems with a full life dose at 25 m of less than 5×10^5 rad (Si) should be pursued.

- Nuclear electric power systems with a very high reliability of full power at the end-of-life should be pursued.

Figure 5-8

FAR OUTER PLANETS ORBITER/PROBE

- PURPOSE

  COMPREHENSIVE SCIENTIFIC EXPLORATION OF URANUS, NEPTUNE AND PLUTO.

- CONCEPT

  INTEGRATED PROGRAM - 3 SEPARATE MISSIONS.
  ATMOSPHERIC PROBES AT URANUS AND NEPTUNE.
  MISSION DURATION LESS THAN 10 YEARS.
  HARDWARE COMMONALITY.

- ENABLING TECHNOLOGIES

  ADVANCED PROPULSION, AEROCAPTURE.
  HIGH RATE DATA TRANSMISSION.

- POWER USE

  ELECTRIC PROPULSION (100-200 KWE).

- NUCLEAR BENEFITS

  NEP ENABLES ALL 3 MISSIONS.
  LARGE PAYLOAD CAPABILITY.
  FLEXIBLE MISSION PLANNING.

- NUCLEAR CONCERNS

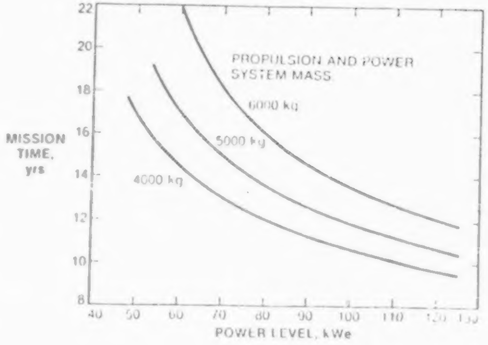
  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

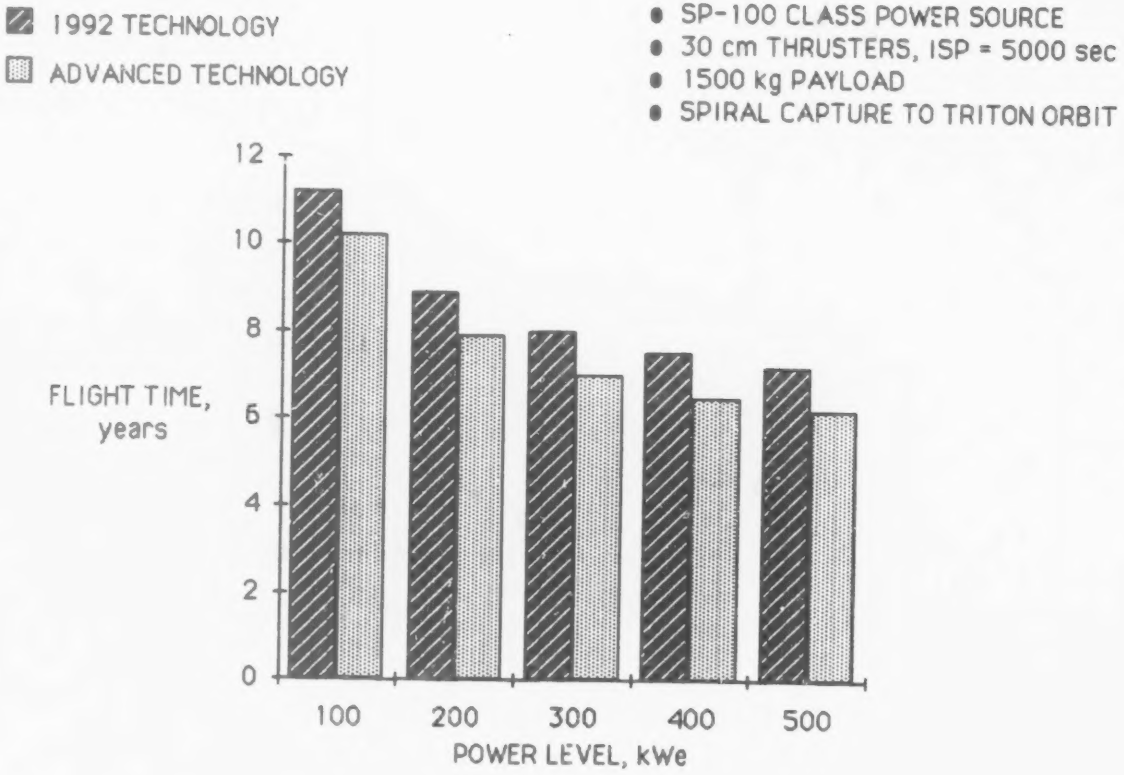
- KEY PERFORMANCE TRADE

  TRIP TIME vs POWER LEVEL.

NEPTUNE ORBITER

- SP-100 NUCLEAR POWER SOURCE
- 1500 kg (S/C AND SCIENCE) PAYLOAD
- SPIRAL CAPTURE TO TRITON FINAL ORBIT





- SP-100 CLASS POWER SOURCE
- 30 cm THRUSTERS, ISP = 5000 sec
- 1500 kg PAYLOAD
- SPIRAL CAPTURE TO TRITON ORBIT

FIGURE 5-9 NEPTUNE ORBITER PERFORMANCE AT HIGHER POWER LEVELS

Table 5-2

POTENTIAL NEP PLANETARY MISSIONS

MISSION	POWER AND PROPULSION SYSTEM MASS	POWER	FULL POWER LIFE	MISSION TRIP TIME	PAYLOAD
NEPTUNE ORBITER	4500 kg	100 kWe	5.9 yrs	11 yrs	1500 kg IN 15.8 R_N ORBIT
SATURN RING RENDEZVOUS	4500	100 kWe	5.9	10.1	1500 kg IN 1.1 R_S ORBIT
MARS SAMPLE RETURN	4000	100 kWe	3.6	4.2	1000 kg/200 kg AT MARS
JUPITER SATELLITE TOUR	4500	100 kWe	5.9	8.0	1500 kg/300 kg PROBES
VENUS ORBITER	4000	100 kWe	2.0	2.0	3000 kg/1000 km CIRCULAR
MERCURY ORBITER/LANDER	4000	100 kWe	3.0	3.0	1500 kg/500 km CIRCULAR
VESTA SAMPLE RETURN	4000	100 kWe	2.4	3.8	1500 kg/100 kg SAMPLE
TEMPLE 2 SAMPLE RETURN	4000	100 kWe	3.4	4	1500 kg/100 kg SAMPLE

ASSUMES A Hg ION PROPULSION SYSTEM AT 5300 sec AND 78% EFFICIENCY

6. PUBLIC SAFETY AND THE USE OF NUCLEAR REACTORS IN SPACE

Safety of flight and ground test systems is universally considered critical to the success of the space nuclear power development program. Accordingly, safety is given the highest priority in the SP-100 Program to ensure that minimum acceptable risk is presented to the general population, the environment, mission personnel, facilities, and equipment. A Surety* Program Plan that includes safety is being finalized which will cover all safety aspects of space nuclear power system technology from conceptual design and development through testing and deployment to ultimate disposal. A Safety Advisory Committee has been established to advise the project on safety and safeguard matters and other aspects of the project which may relate to safety. Safety issues, analyses, and tests will be identified and the impact of safety on all elements of the program will be clearly defined in the Safety Program Plan.

6.1 Management Structure

The SP-100 safety program places safety responsiblity on line management beginning with the Program Director and Program Office down the management chain through the Project Office to the system contractor management. The Program Director is responsible to the Steering Committee for the execution of the SP-100 Program and its plans, including safety. The Surety Program Management is the vehicle for assuring that NASA aerospace safety requirements and regulations as well as DOE nuclear safety requirements and regulations are adhered to within the SP-100 program.

At the Project Office level, the Deputy Project Manager for Nuclear technology, appointed by DOE and responsive to the Program Office through the Project Manager has the responsibility for ensuring the development and implementation of safety strategy and plans at the project level. The Los Alamos National Laboratory (LANL), in support of the Deputy Project Manager for Nuclear Technology, is primarily responsible for developing and implementing the safety strategy and plans that are responsive to SP-100 policy established by the program office. LANL is also responsible, in support of the Deputy Project Manager for Nuclear Technology, for overseeing the SP-100 contractor's safety efforts during the technology assessment and advancement phase. The Safety Advisory Committee (SAC) is an established independent group of safety professionals, reporting to the Project Office, which provides independent assessment of and advice regarding technical and administrative safety and safeguard matters.

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* Surety is an integration of safety, safeguards, environmental protection, reliability, and quality assurance.

At the Program Office level, the Deputy Program Directors for Nuclear and Aerospace Technology from DOE and NASA together with other DOE and NASA resources and staff, serve in an assist role to the Program Director in ensuring/providing an independent technical safety resource for the program. Included in that role is the responsibility for providing an independent overview of the SP-100 Surety Program to assure that DOE and NASA safety responsibilities and regulations are implemented. At both the Program and Project Office levels support contractors may be utilized to help assist with and assure that an independent overview of the safety program is achieved. Figure 6-1 depicts the overall SP-100 Surety Program Management Organization.

6.2 Goals of Safety Program

The primary objective of the safety program is to ensure that the public is adequately protected from radiation, even in the event of accidents. This can be accomplished by: 1) precluding accidental reactor criticality, and 2) preventing the release of levels of radioactive byproducts into the biosphere which exceed established standards.

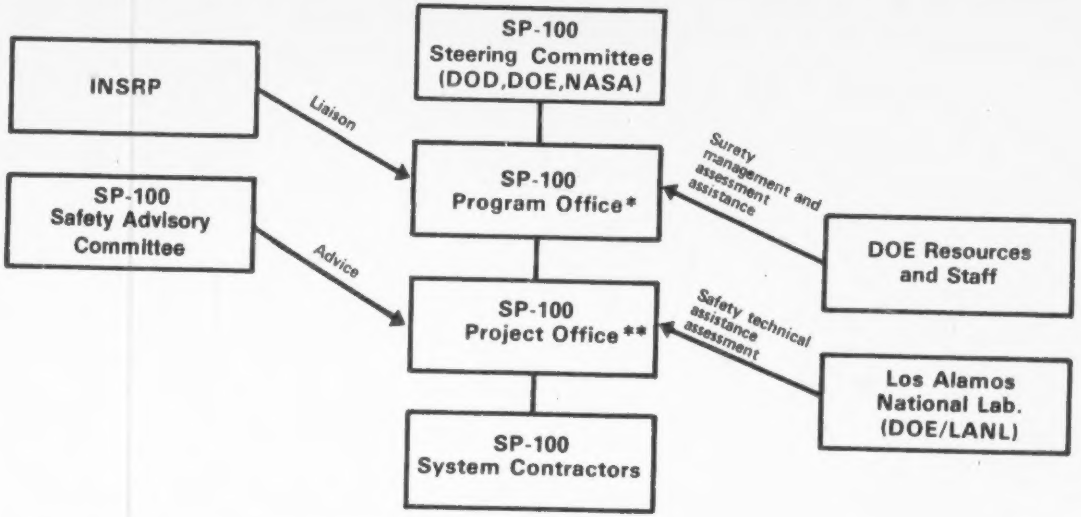
Another set of safety goals encompasses the protection of special nuclear materials and investments in both ground and space facilities. Such resources must be protected, even in case of a failure. Thus, solutions to these problems must be provided without sacrificing public safety or environmental protection.

6.3 Design and Operational Aspects of Safety Achievement

It is essential, from initiation of the design process through final qualification and flight, that space nuclear reactors be designed, fabri-

Figure 6-1

SP-100 SURETY PROGRAM MANAGEMENT ORGANIZATION


INSRP
SP-100 Safety Advisory Committee
Liaison
Advice
SP-100 Steering Committee (DOD,DOE,NASA)
SP-100 Program Office*
SP-100 Project Office**
SP-100 System Contractors
Surety management and assessment assistance
Safety technical assistance assessment
DOE Resources and Staff
Los Alamos National Lab. (DOE/LANL)

* Includes Deputy Program Directors for Nuclear and Aerospace Technology who assist the Program Director concerning SP-100 Surety.

** Includes Deputy Project Manager for Nuclear Technology who has primary responsibility for ensuring adequate planning and execution of surety activities at the Project Office level.

NASA

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cated, tested and employed with public health and safety goals firmly established. The basic philosophy of designing for nuclear safety embraces the following accepted and proven approaches: 1) confine and contain; 2) delay and decay; and 3) dilute and disperse. The confine and contain approach involves isolation via the incorporation of adequate design barriers. The delay and decay approach involves providing sufficient isolation time during which radioactive levels are permitted to adequately decrease naturally to meet established radiation safety standards before any exposure is permitted. This technique is used for space reactors by inserting them into long-life orbits. The dilute and disperse approach is used to reduce concentration levels when exposure is unavoidable and a large medium for dispersal and dilution is available. This approach can also be used for space reactors, particularly ones operated in short-lived orbits, to adequately disperse the fuel, activated substances, and fission products over a wide area, in the event of reentry into the atmosphere, such that radioactivity concentrations meet the established safety standards. All of the methods can be used to meet radiological standards, and several combinations may be used in different parts of a particular mission.

Safety standards are met by design and/or operational features. Design features involve intrinsic hardware devices or elements to preclude potential problems, such as unplanned reactor criticality, until a satisfactory space orbit is attained. Operational features, on the other hand, involve procedures to avoid potential problems such as not operating the reactor at substantial integrated power levels prior to launch (and, thus, not building up any appreciable fission product inventory), and not starting the reactor until the specified desired orbit is reached.

The entire spectrum of accident environments must be considered; these must apply to each and every phase of the planned development process and mission. Based on the launch vehicle and mission profile, actual environmental conditions and the system response must be determined for each postulated accident.

Table 6-1 lists goals, reasons for the goals, and design requirements presently in place to meet these goals (Ref. 6-1). Each of these will be discussed in terms of the design and operational features now being considered in the SP-100 power plant conceptual designs.

The fuel, as long as it is substantially unirradiated, represents no appreciable radiological hazard. However, since highly enriched uranium is used in the current reactor designs, and it does represent a potential criticality hazard and safeguard concern, handling of the fueled reactor will be under established Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) procedures and regulations. These encompass physical security, materials control and accounting, and inspection to verify materials inventories and to ensure adequate subcriticality. As an example, physical protection measures are regulated by DOE Order 5632.2 and materials control and accountability measures by Order 5630.2. DOE regulations also exist for fabrication, assembly, testing, transportation and pre-launch storage; these will probably not have a direct impact on the flight system design. Under normal conditions on the launch pad, it is expected that reactor power plants can be handled in essentially the same manner as other high-value cargo for the Space Shuttle.

Once on the launch pad, certain features are currently planned to be used to protect workers and astronauts. Radiological levels will be so low that no special exclusion zones will need to be established. This is easily achieved by using fuel that has not been appreciably irradiated and, thus, its intrinsic radiation levels would be significantly below safety standards. That is, the operating history of the reactor will be such that any criticality testing will be sufficiently short as to avoid any appreciable fission product buildup. Nevertheless radiation detection equipment will be used by personnel in the vicinity of the reactor as monitors to verify that safety standards are being met. Another design feature is that the control elements will be locked into their most neutron absorbing (shutdown) position. On the order of twelve or more control elements (i.e., rotating drums) are currently included in the various 100 kWe class design concepts. Provision to allow for single drum testing, one at a time, is expected but this will not generate a criticality

Table 6-1

SAFETY GOALS AND REQUIREMENTS

GOALS	REASONS	DESIGN REQUIREMENTS
NORMAL CONDITIONS PRIOR TO LAUNCH TO AVOID SPECIAL HANDLING OR PRECAUTIONS	PROTECT WORKERS AND ASTRONAUTS	NOT OPERATE REACTOR (EXCEPT FOR ZERO POWER TESTING) UNTIL A STABLE ORBIT OR FLIGHT PATH IS ACHIEVED.
		TWO INDEPENDENT CONTROL/SHUTDOWN SYSTEMS TO REDUCE REACTIVITY TO A SUBCRITICAL STATE OR MAINTAIN SUBCRITICALITY.
		UNIRRADIATED FUEL SHALL POSE NO SIGNIFICANT ENVIRONMENTAL HAZARD.
PREVENT INADVERTENT CRITICALITY	INSURE PUBLIC NOT EXPOSED TO LEVELS OF RADIATION THAT EXCEED STANDARDS.	SUBCRITICAL IF IMMERSED IN WATER OR OTHER FLUID.
	PROTECT SHUTTLE CREW	SIGNIFICANT NEGATIVE POWER COEFFICIENT.
		SUBCRITICAL ON EARTH IMPACT. INCORPORATE A REACTOR SAFETY SYSTEM QAULITY ASSURANCE STANDARDS.
		POSITIVE CODED TELEMETRY FOR REACTOR STARTUP.
		REDUNDANT CONTROL AND SHUTDOWN SYSTEMS.
		INDEPENDENT SOURCE OF ELECTRICAL POWER FOR REACTOR CONTROL SYSTEM, REACTOR PROTECTION SYSTEM, REACTOR COMMUNICATION SYSTEM.
		INSTRUMENTATION TO CONTINUOUSLY MONITOR REACTOR STATUS.

Table 6-1 (cont'd.)

SAFETY GOALS AND REQUIREMENTS

GOALS	REASONS	DESIGN REQUIREMENTS
PREVENT RELEASE OF RADIOACTIVITY IN CONCENTRATIONS EXCEEDING RADIOLOGICAL STANDARDS.	INSURE PUBLIC NOT EXPOSED TO RADIATION LEVELS THAT EXCEED STANDARDS AND PROTECT BIOSPHERE AGAINST CONCENTRATION OF RADIOACTIVITY ABOVE SAFETY STANDARDS	ORBITAL BOOST SYSTEM FOR SHORT-LIVED ORBITS; REACTOR DISPERSAL, OR, POTENTIALLY, CONTAINMENT INTEGRITY, IF BOOSTER FAILS (PRIMARY CONCERN IS RADIOLOGICAL; SHORT-LIVED ORBITAL MISSIONS) SPACECRAFT ATTITUDE CONTROLLER FOR COMMUNICATIONS AND BOOST SYSTEM.
AVOID UNPLANNED CORE DESTRUCTION	PROTECT SPACE INVESTMENTS AND AVOID CONTAMINATION OF VOLUMES OF SPACE ENVIRONMENT	INDEPENDENT/REDUNDANT SHUTDOWN HEAT REMOVAL SYSTEMS FOR DECAY HEAT REMOVAL. TWO INDEPENDENT SYSTEMS TO REDUCE REACTIVITY TO A SUBCRITICAL STATE OR MAINTAIN SUBCRITICALITY. POSITIVE CODED TELEMETRY SIGNAL TO OPERATE REACTOR. TWO INDEPENDENT REACTOR PROTECTION SYSTEMS. FAULT DETECTION SYSTEMS FOR REACTOR PROTECTION SYSTEMS. SIGNIFICANT NEGATIVE POWER COEFFICIENT.

or radiological risk condition even if a drum is fully rotated to its minimum neutron absorption position. The lock system on the reactivity control system is not planned to be removed prior to the Shuttle achieving orbit. Such locks could be mechanical, requiring astronaut actions for their removal, or electronic, requiring independent, coded telemetry signals for removal.

Inadvertent reactor criticality is to be prevented, even under accident conditions, to protect workers, astronauts, and the public against exposure. Design requirements to achieve this goal are given in Table 6-1. Design features to maintain subcriticality in water or other available fluids (e.g., liquid hydrogen in a launch accident situation) include the incorporation of additional neutron absorbing control materials, e.g., a central neutron absorber element that is withdrawn once orbit is reached in one design concept and distributed core control rods in another concept. The additional neutron absorber, regardless of the arrangement, is designed to insure that the reactor will remain subcritical regardless of the fluid it might accidentally be immersed in. The significant negative power coefficient requirement is met by design and ensures that as power or temperature rises, control and safety are intrisically provided via a negative reactivity feedback effect. Subcriticality on Earth impact can be facilitated by mechanical design features such as an arrangement of the reflector in segments and using rings for support. Design features of all the reactors under consideration include redundant reactivity control systems such that a malfunction in one will not lead to inadvertant criticality nor will it prevent the reactor from being shut down. It has been mentioned that at least twelve control drums with separate electro-mechanical actuators are part of the reactor designs. These actuators typically incorporate a brake mechanism and a separate "scram" actuating mechanism. The scram provision is such that the system will fail-safe. That is, if power is lost, the actuator will automatically operate (e.g., via a spring) to position the neutron absorber in the shutdown position. Also, the brake is intended to prevent movement of the actuator without the spring being set. Independent and redundant controls and instrumentation are required to insure against single failures being able to start the reactor once the drum locks and in-core reactor absorbing element are removed. An additional precaution against unintentional criticality is the use of positive coded telemetry signals to ensure only positive intentional startup after an adequate orbit is attained.

The public is protected against radioactive products both by design and operational features, via the employment of confinement and containment, delay and decay, and/or dilution and dispersion nuclear safety approaches. Generally, reactor power plants will be operated in long-lived orbits so that delay and decay would be operative. These are presently defined as orbital lifetimes of at least 300 years. This time interval allows for most of the radioactive by-products to undergo substantial decay prior to potential reentry into the biosphere. (Levels decrease from 10^7 to 10^2 Curies in that time.) The reactor design can also incorporate features that will result or cause the core to remain intact or undergo adequate dispersal upon reentry. Radiologically, this is of particular concern for short-lived orbital missions. The dispersal and containment options driven by both safeguards and radiological concerns, i.e., to ensure standards are met. Additionally, if a reactor is used below the long-lived orbit, a boost system will be incorporated to move it above the 300 years orbit lifetime at the end of its productive life. This poses an additional radiological concern in that, if near-term reentry occurs at the end of the system's useful life due to boost system failure, the reactor fission product inventory must be either contained or dispersed sufficiently to ensure that radiological standards are met. To insure that the safety boost system can be operated with a high degree of reliability, a special spacecraft attitude controller is to be included for communications and orientation verification.

Our space investment runs into the billions of dollars and must be protected. This is especially true for the Space Station. To meet this goal, redundant elements are planned in the design for decay heat removal. Also, independent reactor control and shutdown protection systems and a significant negative power coefficient are incorporated into the concept designs. These include fault detection and overrides to avoid destruction of the reactor during operation.

6.4 Approval and Documentation Process

Review, approval, and documentation requirements developed primarily for space radioisotope systems can be readily expanded to include space nuclear reactor power systems (Ref. 6-2). The required approval steps and documentation are summarized in Figure 6-2. Two key documents are required relatively early in any space nuclear source development program: The Nuclear Safety Criteria and Specification document, and the Program Safety, or Surety, Plan. An early form of both have already been issued. (See, for example Ref. 6-1).

The Program Safety, or Surety, Plan provides an overall plan for formulating, integrating, and achieving all necessary safety elements of the program required to meet safety objectives and eventually to obtain flight approval. More specifically, it provides the logic and strategy for safety assessment, analysis, and testing in support of the critical technology development phase of the program. Included are comprehensive, systematic analyses to identify the full spectrum of safety issues that could occur over the life of the program and mission, and logic and rationale for any tests or analyses required to resolve the critical issues. Safety is considered in all phases of the program, i.e., design phase, development phase, test phase, transportation/ground handling phase, as well as all mission phases. Therefore, the Program Surety Plan is being prepared early in the SP-100 program to assure timely consideration of safety issues.

The role of the Interagency Nuclear Safety Review Panel (INSRP) is described in Figure 6-3. The INSRP has members not only from DOD, NASA, and DOE, but also from various active working groups. Many scientists and engineers from government agencies, laboratories, and universities will assist in the review. These specialists will evaluate the required Safety Analysis Reports and perform independent calculations and tests as required by the INSRP.

Once the Final Safety Analysis Report has been reviewed and the INSRP members are satisfied, the panel will prepare a Safety Evaluation Report (SER) and submit it to agency heads for review and approval. Although the

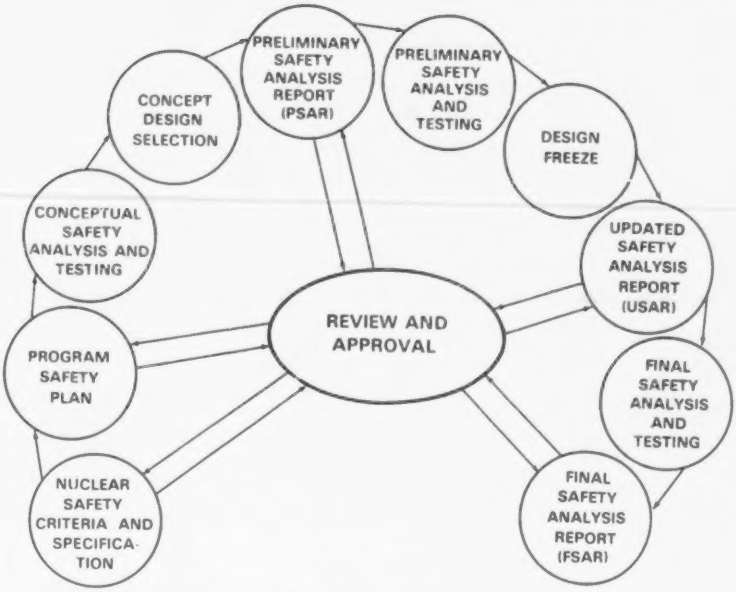
PRELIMINARY SAFETY ANALYSIS REPORT (PSAR)
PRELIMINARY SAFETY ANALYSIS AND TESTING
CONCEPT DESIGN SELECTION
DESIGN FREEZE
CONCEPTUAL SAFETY ANALYSIS AND TESTING
UPDATED SAFETY ANALYSIS REPORT (USAR)
REVIEW AND APPROVAL
PROGRAM SAFETY PLAN
FINAL SAFETY ANALYSIS AND TESTING
NUCLEAR SAFETY CRITERIA AND SPECIFICATION
FINAL SAFETY ANALYSIS REPORT (FSAR)

Figure 6-2 Nuclear Safety Approval Steps and Documentation

NASA HQ RS84-1388(1)
4-11-84

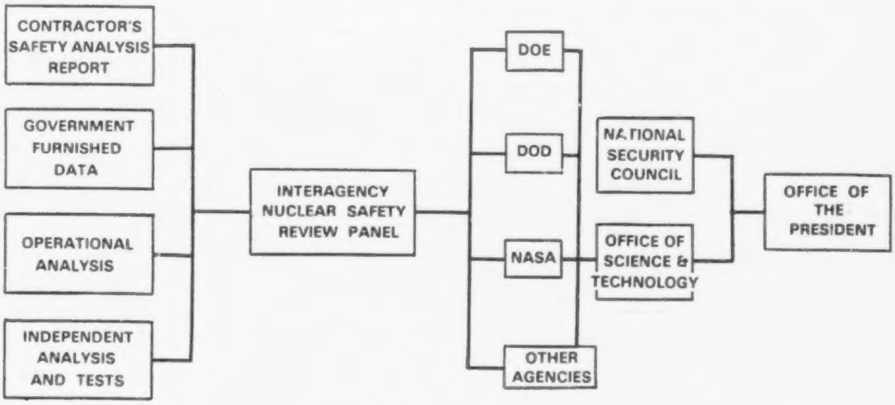
CONTRACTOR'S SAFETY ANALYSIS REPORT
GOVERNMENT FURNISHED DATA
OPERATIONAL ANALYSIS
INDEPENDENT ANALYSIS AND TESTS
INTERAGENCY NUCLEAR SAFETY REVIEW PANEL
DOE
DOD
NASA
OTHER AGENCIES
NATIONAL SECURITY COUNCIL
OFFICE OF SCIENCE & TECHNOLOGY
OFFICE OF THE PRESIDENT

Figure 6-3 Safety review and launch approval process.

NASA HQ RS84-1390 (1)
REV. 4-24-84 24

INSRP will not make a recommendation for launch approval or disapproval, the results of the INSRP review, as documented in the SER, certainly will be a factor used by agency heads in making that decision. After the SER has gone to the agency heads and they are satisfied with the findings, the supporting agency heads will submit letters of concurrence to the user agency. In turn, the user agency will submit letters to the Office of Science and Technology Policy requesting launch approval. This request may be acted on at that level or, in some cases, in the Office of the President.

6.5 SP-100 Surety Program Plan

The SP-100 Surety Program will provide confidence that safety will be adequately integrated into the design and that flight approval can ultimately be obtained while minimizing undue design penalties/implications. To achieve this objective, the Surety Program during the Technology Assessment and Advancement Phase will focus on establishing preliminary safety criteria with supporting technical bases. These preliminary criteria will be approved by the SP-100 Program Office and reviewed by appropriate independent bodies to ensure that there is a broad consensus by July 1985. In addition, for each phase of the SP-100 Development Program, the feasibility of, or actually demonstrate compliance with, meeting the safety, safeguards, and environmental protection criteria by producing a technical base of analysis and test results, reviewing contractor results, and performing independent analysis and testing as required will be established. Where feasibility cannot be demonstrated by July 1985, open issues and potential resolution paths will be identified for resolution in phase II of the Development Program.

To aid in a comprehensive and systematic investigation of safety issues and issue resolution planning, the safety program has defined phases that the SP-100 hardware is expected to progress through. Accordingly, the SP-100 safety program has been divided into six sequential but distinct safety issue planning phases:

1. Ground Testing Phase

Once the design concept has been selected and approved, the construction of a test unit would begin. Construction and testing of this unit and evaluation of the test results will constitute the ground testing phase.

2. Transportation/Ground Handling Phase

It is assumed that SP-100 will be constructed at a contractor facility and transported to the launch site (transportation phase). The ground handling phase includes construction, loading and removal of the SP-100 from the transportation vehicle, storage, preflight testing, loading into the shuttle bay, transport to the launch area (if it is loaded in the vehicle assembly building), and initiation of the Launch Phase.

3. Launch Phase

This phase starts with liquid propellant loading of the Shuttle, and any on-board orbital transfer stage, through launch pad lift-off.

4. Ascent Phase

This phase covers the time period from launch pad lift-off through the Shuttle attaining stable orbit and SP-100 deployment.

5. Operational Phase

Includes the time required to first bring the reactor critical through end-of-life shutdown.

6. End-of-Life Disposition Phase

This phase covers the time from end-of-life shutdown to its ultimate disposition at some future date.

These planning phases have been prioritized, and the issues within each planning phase have been identified and prioritized as well. The priorities were established based on the potential of a planning phase or issue to:

- Have a major influence on the SP-100 design, (critical in the early stages of the program)

- Affect flight approval,
- Be a critical path item or have large resource requirements, and
- Produce large safety consequences.

The launch, ascent, and end-of-life disposition planning phases, respectively, have been identified as the highest priority phases because these have a strong potential to result in design modifications - critical at this point in the Program.

The SP-100 could be exposed to high temperatures, extreme overpressures/shock, high velocity impacts, and high velocity missile impacts in the event of an accident. The objective will be to develop comprehensive, acceptable, defendable, and unambiguous safety criteria that reflect safety policy and protect the general population and the environment but do not involve undue design penalties and implications. The overall focus of the safety program is to ultimately achieve both a real and perceived protection of public health, the environment, the special nuclear material and other resources while not imposing undue design penalties/implications.

A comprehensive set of safety issues and criteria is being developed. The safety issues will be fully characterized with respect to the effects on the current SP-100 designs. Potential design penalties/implications for compliance to safety criteria need to be qualified. These potential design penalties must be evaluated against the overall safety, safeguards, quality assurance, reliability, and environmental protection implications and risks. Then the optimum path for resolution can be clearly established.

The near-term objectives of the SP-100 safety program are to: 1) ensure that a comprehensive and technically defensible set of preliminary safety criteria is established, agreed upon, and available in July 1985 as the program enters the Engineering Development and Ground Testing phase; 2) identify testing needs for the Ground Engineering System Test Phase of the Program; and 3) establish the safety feasibility of the design(s).

6.6 Concluding Remarks

The following points are made in summary and conclusion of safety issue considerations:

- Public safety is of primary concern from design initiation through flight and final disposal.
- An initial set of safety standards has been established and a plan to insure compliance is being developed.
- A stringent review and approval process exists for space radioisotope systems that forms the bases for reactor systems.
- Design and operational features will be used in space nuclear power plants to meet safety requirements.
- Current emphasis is being placed on launch, ascent and end-of-life disposal phases because: These have been assessed to have a major influence on the design; affect flight approval; be a critical path item or have large resource requirements; and produce significant safety hazards.

7. SUMMARY AND CONCLUSIONS

In summary, the opinion of the CMAG is that space nuclear power will be an important alternative for use in civil missions in the nineties and beyond. Therefore, the current technology and development programs must incorporate the features specific to civilian applications to avoid time-consuming and costly redesigns later.

The CMAG conclusions as a result of our evaluations are:

- The more detailed review of selected missions confirms our earlier conclusions that electrical power needs will extend over the range from 50 to 1000 kWe and that the civil missions being considered are enhanced, or even possibly enabled, by nuclear power.
- Nuclear electric power is an excellent candidate for the Growth Space Station, especially as power levels grow beyond 300 kWe. In order to be prepared for this use, the current reactor power plant development program must be designed for low orbit environment and manned operations as part of the requirements.
- The multi-functional communications platform and air traffic control missions are enhanced by nuclear power attributes such as lower power cost, independence of solar illumination, flexibility of platform location, and allowing assembly in LEO with nuclear electric propulsion orbit transfer.
- Many planetary missions are enhanced and possibly enabled by nuclear power use in electric propulsion systems. These missions include Neptune orbiters, Saturn ring rendezvous, Mars sample return, Jupiter satellite orbiter/lander tour, Mercury orbiter and lander, and sample return from comets and asteroids such as Tempel 2 and Vesta. Significant benefits are greater payload mass and shorter trip times.
- Public safety must continue to be emphasized from the initial design to final deployment and disposal. The highest level of management attention must be directed to this area in order to avoid costly delays and redesigns later. An adequate start has been made in this direction.

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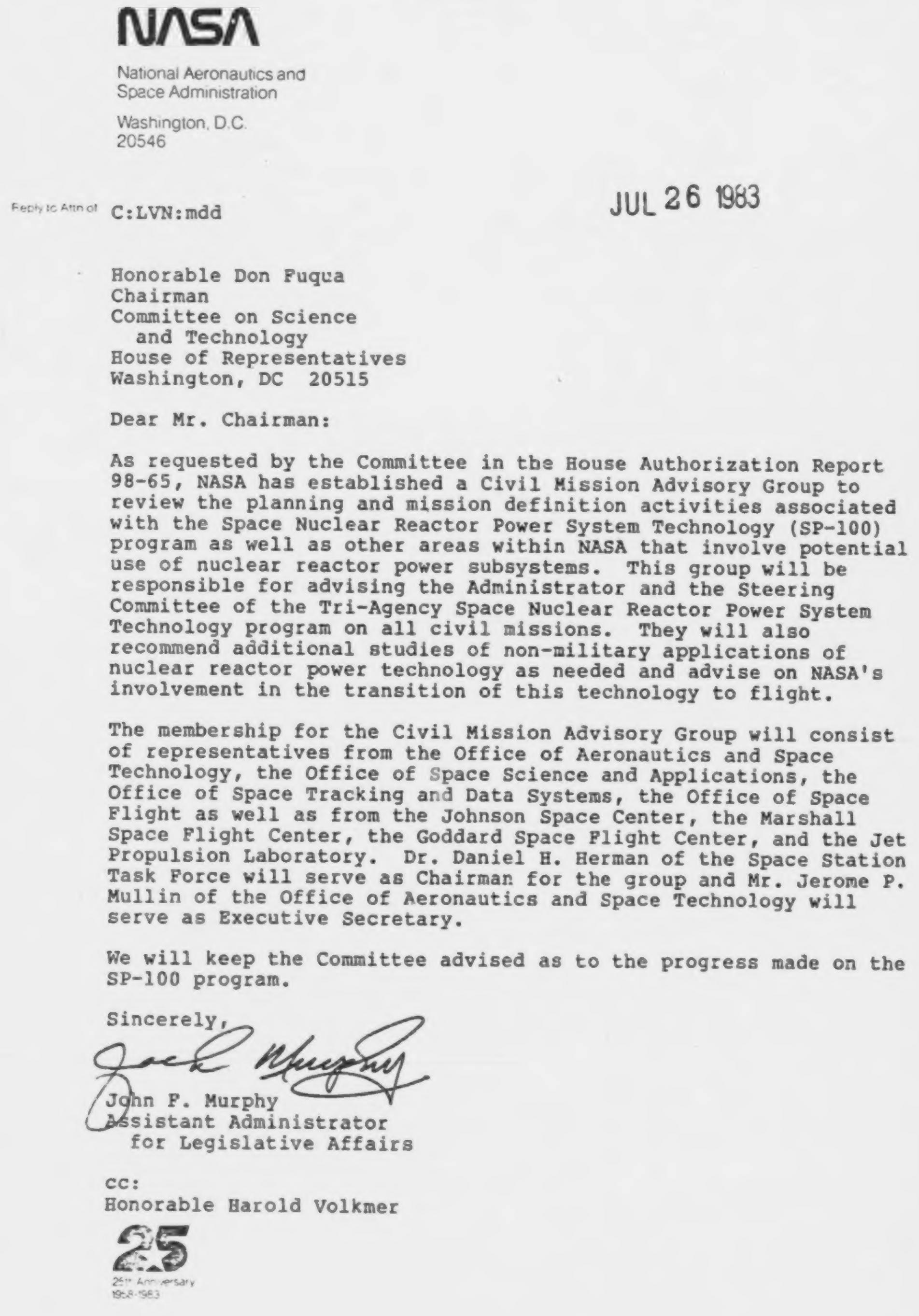
CIVIL APPLICATIONS OF NUCLEAR POWER—INTERIM REPORT OF THE CIVIL MISSIONS ADVISORY GROUP



NASA
National Aeronautics and
Space Administration
Washington, D.C.
20546

Reply to Attn of: C:LVN:mdd

JUL 26 1983

Honorable Don Fuqua
Chairman
Committee on Science
and Technology
House of Representatives
Washington, DC 20515

Dear Mr. Chairman:

As requested by the Committee in the House Authorization Report 98-65, NASA has established a Civil Mission Advisory Group to review the planning and mission definition activities associated with the Space Nuclear Reactor Power System Technology (SP-100) program as well as other areas within NASA that involve potential use of nuclear reactor power subsystems. This group will be responsible for advising the Administrator and the Steering Committee of the Tri-Agency Space Nuclear Reactor Power System Technology program on all civil missions. They will also recommend additional studies of non-military applications of nuclear reactor power technology as needed and advise on NASA's involvement in the transition of this technology to flight.

The membership for the Civil Mission Advisory Group will consist of representatives from the Office of Aeronautics and Space Technology, the Office of Space Science and Applications, the Office of Space Tracking and Data Systems, the Office of Space Flight as well as from the Johnson Space Center, the Marshall Space Flight Center, the Goddard Space Flight Center, and the Jet Propulsion Laboratory. Dr. Daniel H. Herman of the Space Station Task Force will serve as Chairman for the group and Mr. Jerome P. Mullin of the Office of Aeronautics and Space Technology will serve as Executive Secretary.

We will keep the Committee advised as to the progress made on the SP-100 program.

Sincerely,

Jack Murphy

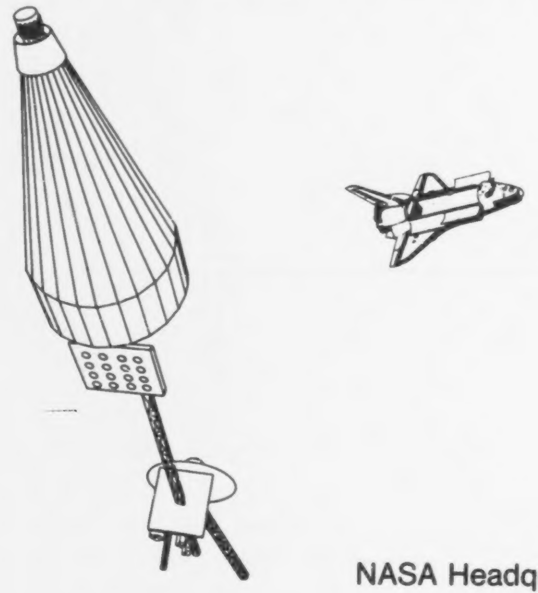
John F. Murphy
Assistant Administrator
for Legislative Affairs

cc:
Honorable Harold Volkmer

25
25th Anniversary
1958-1983

National
Aeronautics and
Space
Administration

Civil Applications Of Nuclear Power - Interim Report Of The Civil Missions Advisory Group



NASA Headquarters
March 1984

CIVIL APPLICATIONS OF SPACE NUCLEAR POWER - INTERIM REPORT OF THE CIVIL MISSIONS ADVISORY GROUP

NASA HEADQUARTERS

MARCH 1984

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1. EXECUTIVE SUMMARY

This interim report of the Civil Missions Advisory Group (CMAG) is intended as a status report of the ongoing examination of nuclear reactor power uses for future missions in the civilian/commercial sector of space applications. CMAG was established by NASA in the third quarter of 1983 to address concerns expressed by the Committee on Science and Technology in House Authorization Report 98-65. These concerns relate to the interface between civil and military use of space reactor power systems, and the timing of future applications. At present, the assessment of space reactor technology and mission applications is being conducted under the SP-100 program which is a tri-agency agreement among NASA, DOE, and DARPA.

To assure the House Committee that civil mission needs are being adequately analyzed and defined, NASA formed and directed CMAG to carry out the following responsibilities: (1) review the mission planning and definition activities associated with the SP-100 program and other areas within NASA that involve potential use of space nuclear power; (2) advise the NASA Administrator and the Tri-Agency Steering Committee on all significant civil missions; (3) recommend additional studies as needed; and (4) advise the Administrator and Congress on NASA's role in the transition of this technology to flight readiness.

Currently, it is sufficient to show that potential civil missions accrue significant benefits with the development of space reactor power systems. This report accomplishes that goal. Narrowing the group of missions to a specific one only becomes necessary at the time of committment to flight power system development. This can be reasonably expected to take place in the late 1980's as critical technology issues are resolved and particular missions are assessed to the degree necessary to permit implementation.

This report focuses on the results of the first phase of the CMAG study, namely, the selected set of civil missions and description of mission objectives and requirements. The findings of CMAG are summarized as follows:

- A broad range of civil missions with high power requirements has been identified. These missions have objectives supported by established goals for space exploration and applications and are likely to be implemented within the next 25 years. The major areas of user community interest and benefit are: Earth and space sciences; public service communications and observational utility; and government/-commercial ventures in space manufacturing and resource utilization.
- The civil mission set considered to be useful for planning purposes is comprised of more than 10 representative missions organized here by generic category or type of applications: manned orbital facility (space station); Earth science and applications; transportation of large payloads; extraterrestrial resources; and planetary exploration.
- The functional use and amount of power required varies widely across the mission set. The dominant use categories are materials processing, electric propulsion, and communications/radar transmission. Electrical power requirements generally range from 50 to 1000 kW, with a number of missions functioning particularly well at the 100-200 kW level. Civil mission energy requirements are further characterized by long-term operations and near-continuous power demand.
- All missions in the set are enhanced by the availability of nuclear power. In several cases the missions are made possible by such systems.

The primary benefits of nuclear reactor systems compared to alternative energy sources are compactness, higher power density, and lower recurring cost. Demonstration of this potential is underway within the current technology assessment program. Additional important benefits are independence of solar illumination conditions, simplified attitude dynamics and control for most missions, and enhanced operational capability in hostile environments. A lien against these benefits is the added mass for shielding sensitive payloads from reactor radiation effects, particularly in the case of manned operations. Finally, nuclear safety must be assured in launch and orbit operations.

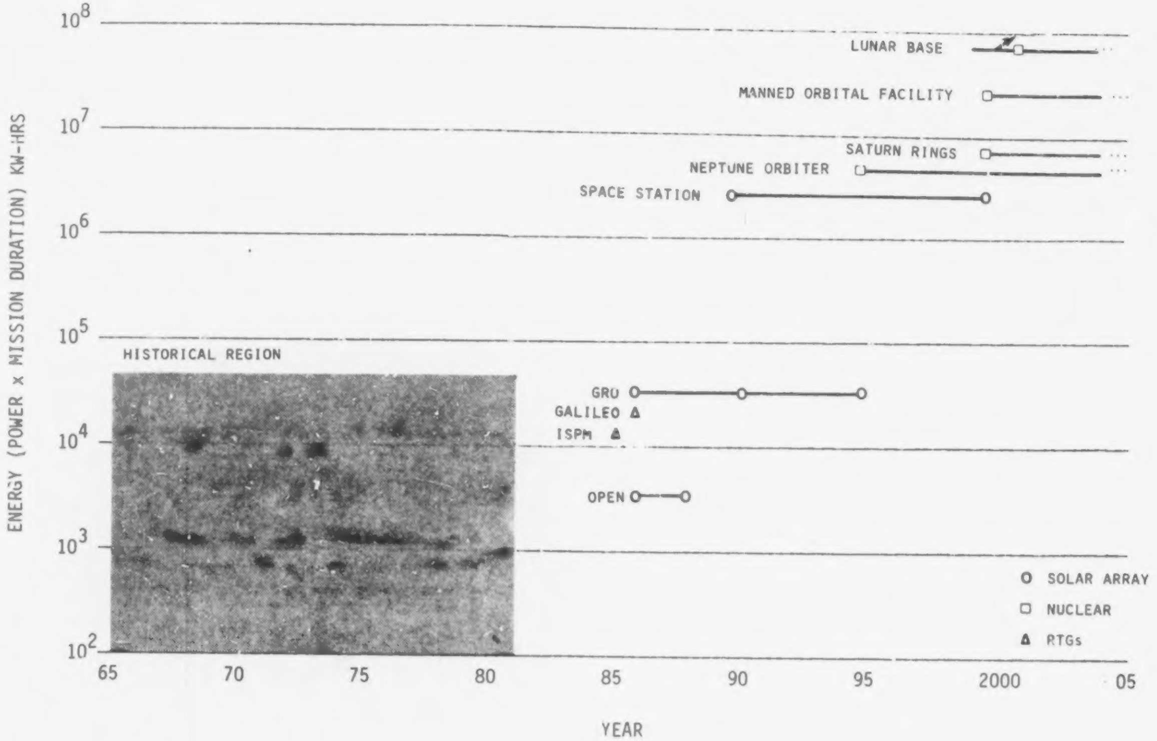
2. INTRODUCTION AND BACKGROUND

Energy needs, primarily in the form of electrical power, have been relatively modest during the first twenty-five years of the Space Age. These needs have been satisfied by well-understood and developed technologies such as photovoltaic (solar) cells with battery storage, chemical fuel cells, and radioisotope thermoelectric generators. Typical power demands of spacecraft during this era were in the range 100-1000 watts with total energy (power times mission duration) requirements as low as 100 kWe-hours and seldom ever exceeding 50,000 kWe-hours. Power subsystem weight and cost per watt (or per kW-hour) of electrical output have remained relatively high even with recent improvements. While this situation may have been acceptable in modest demand scenarios and when placed in context of total mission weight and cost, it will not be so for the next generation of space missions. Realization of the future promise will require the development and use of power systems having higher efficiency, lighter weight, longer lifetime, greater reliability, and lower cost.

It is reasonable to project an accelerating growth in space activities during the next few decades brought about by real and perceived mission need in combination with available new technology. Much of this activity will require large amounts of power, either to implement the primary mission goals or to satisfy the means of payload delivery. A variety of mission applications have been conceived and are being planned in such areas as space sciences and planetary exploration, Earth observation and communications, manned orbital stations, and commercial ventures in space manufacturing and resource utilization. Figure 1 illustrates the energy requirements for a number of potential future missions and compares these with the historical base through the early 1980's. Typical energy levels for such missions are between 1 and 100 million kWe-hours with corresponding peak power requirements between 50 and 1000 kWe. It is evident that the orders of magnitude increase projected for future energy and power demands will present an enormous challenge to both technology development and systems design. These two discipline areas traditionally trade off against each other in the selection process since they strongly impact mission performance, operational support requirements, affordability, and manageability.

Figure 1

FUTURE SPACE ENERGY DEMANDS



2.1 Benefits of Nuclear Power

Space power systems development will likely follow two concurrent paths depending on the application requirements and time period of interest. One path will focus on the evolutionary development of current approaches such as improved solar cells, concentrating-array elements, and more efficient energy storage devices. The second path will involve new developments in advanced, mission-enabling technologies such as solar-dynamic and nuclear reactor power systems.

Studies of competing energy sources suggest that nuclear reactor systems have the potential of being less massive and more economical than solar array systems for high power applications. These primary benefits are complemented by several other advantages in the operational environment of a power system and its host space vehicle. A space reactor system is inherently independent of the Sun and thus can operate on a full duty cycle without needing large energy storage devices during eclipse or local night conditions. Solar independence also implies a simplified attitude control requirements which may allow improved accuracy for instrument pointing and target tracking. Nuclear systems have a much smaller cross section area than solar array power sources. This attribute results in several important benefits: (1) reduction in drag-makeup propellant required to maintain altitude in low Earth orbit applications, (2) lower risk of damage due to meteoroid or space debris impacts, (3) better field-of-view for pointed experiments, and (4) less interference for large structures assembly operations. Another benefit to be noted is that the inherent "hardness" of a nuclear system enhances survival in contaminating environments and, in particular, allows operation in natural radiation fields (e.g. Van Allen Belts) without suffering degradation of power output.

2.2 Space Nuclear Power History

Nuclear power development and flight programs in the U.S. attained a high level of activity from the mid-1950's to the early 1970's. The Systems for Nuclear Auxiliary Power (SNAP) Program provided the early and continued development of radioisotope thermoelectric generators (RTG) with the first operational launch in 1961. A total of 23 nuclear-powered spacecraft serving NASA and DOD needs have been launched to date. All power sources except one (SNAP 10-A) were RTG's. SNAP 10-A was a small nuclear reactor system launched in 1965 and successfully produced 500 watts of electrical power for 43 days until shut down by its parent spacecraft.

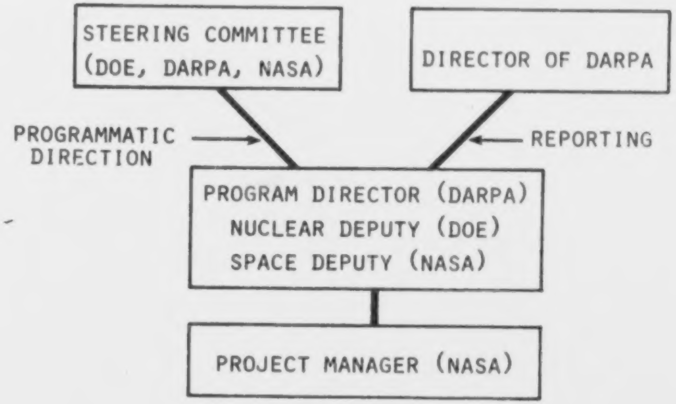
The conception of high-power space reactors dates back to the Rover Program initiated in the mid-1950's. Rover was a nuclear rocket propulsion system researched at the Los Alamos (LASL) National Laboratory with engineering development by industry in the NERVA program. This system was initially intended to be used as an ICBM second stage, however, the major activity centered on propulsion for manned space exploration. Neither version was flown as a result of revised priorities. Subsequent efforts in large space reactors have been carried out by DOE and NASA with focus on technology advancement, design, and test of reactor components and systems. The "keep alive" program from 1973 to 1983 also funded several studies in mission analysis and future applications of nuclear systems. In the meantime, more than 20 Soviet satellites have been flown with nuclear reactor power sources.

2.3 SP-100 Technology Assessment Program

A growing awareness of high-power mission applications, both civilian and military, led to formation of the tri-agency SP-100 program in 1983. This program is defined by an agreement between NASA, DOE and DARPA to carry out a comprehensive assessment of space nuclear reactor technology leading to a possible decision to undertake engineering development. The management structure of this program is described in Figure 2. SP-100 is not focused on a pre-defined level of power output, but rather is investigating technology requirements for both a 100 kWe-class reactor and multi-megawatt systems. Objectives of the SP-100 activity are to obtain a better definition of mission applications and requirements, to evaluate alternative system designs, to identify critical technology problems and workable solutions, to ensure that safety is fully considered, and to plan a subsequent phase of engineering development. The first phase of this

Figure 2

SP-100 PROGRAM


STEERING COMMITTEE (DOE, DARPA, NASA)
DIRECTOR OF DARPA
PROGRAMMATIC DIRECTION
REPORTING
PROGRAM DIRECTOR (DARPA)
NUCLEAR DEPUTY (DOE)
SPACE DEPUTY (NASA)
PROJECT MANAGER (NASA)

- SAFETY
- MISSION AND SYSTEMS PERFORMANCE
- 100 kWe CLASS TECHNOLOGY
- MULTIMEGAWATT TECHNOLOGY
- DEVELOPMENT PHASE PLANNING

TECHNOLOGY PHASE

	FY 83	FY 84	FY 85
MEMORANDUM OF AGREEMENT	▼		
INTERMEDIATE REVIEW		▼	
GROUND TEST PHASE DECISION			▽
BUDGET (MILLIONS OF DOLLARS)	11.4	15.6	16.0

program extends through FY-1985 and will provide the technical basis for deciding whether or not to proceed further.

2.4 Civil Missions Advisory Group

The Civil Missions Advisory Group (CMAG) was established by NASA in the third quarter of 1983 to address concerns expressed by the Committee on Science and Technology in House Authorization Report 98-65. These concerns relate to the interface between civil and military use of space reactor power systems, and the timing of future applications. Qualified representatives from Headquarters and NASA field centers were selected for this assessment task. The membership of CMAG and its schedule of activities are shown in Figure 3. The objectives and responsibilities of CMAG are as follows:

1. Review the planning and mission definition activities associated with the SP-100 program.
2. Advise the NASA Administrator and the Steering Committee of SP-100 on all significant civil missions.
3. Recommend additional studies, as needed, of non-military applications of nuclear reactor power technology.
4. Advise the Administrator and Congress on NASA's role in the transition from technology development to flight operations.

CMAG is in the process of carrying out these responsibilities through its directed requests for technical information, deliberations at working group meetings, and preparation of report materials. This is an Interim Report describing the selected set of civil missions and their requirements. A final report of this advisory group will subsequently be published in September 1984 and will address additional key issues associated with the development and use of space nuclear power systems.

Figure 3

CIVIL MISSIONS ADVISORY GROUP (CMAG)

- RESPONSE TO CONGRESSIONAL CONCERNS EXPRESSED IN HOUSE AUTHORIZATION REPORT 98-65:
  - REVIEW PLANNING AND MISSION DEFINITION ACTIVITIES ASSOCIATED WITH THE SP-100 PROGRAM
  - ADVISE THE ADMINISTRATOR AND THE STEERING COMMITTEE OF SP-100 ON ALL CIVIL MISSIONS
  - RECOMMEND ADDITIONAL STUDIES, AS NEEDED
  - ADVISE ON NASA'S INVOLVEMENT IN THE TRANSITION OF TECHNOLOGY TO FLIGHT

CMAG MEMBERSHIP

CHAIRMAN:	
DANIEL H. HERMAN	SPA. STA.
EXEC. SECY:	
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MEMBERS:	
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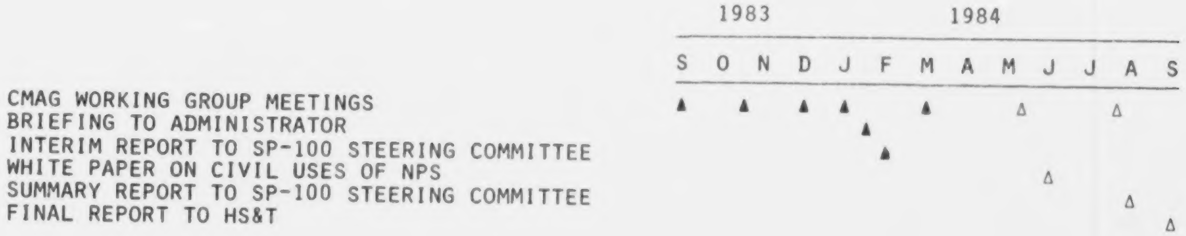

3. CIVIL MISSION APPLICATIONS

A wide variety of mission applications serving the civilian (non-military) sector have been proposed, some of which have received considerable analysis and planning attention while others are preliminary concepts. The range of potential, high-power missions encompasses such areas as Earth science and applications, solar system exploration, and commercial ventures in space manufacturing and resource utilization. Program development and user communities include government agencies, universities, and the private business/citizen sector in the U.S., and possibly other nations as well.

A key role assigned to CMAG is to conduct a deliberate investigation of potential civil missions with a view toward identifying significant applications for high-power demands in general, and space nuclear power in particular. The objective is to assess various input sources of information in order to arrive at a representative (but not necessarily inclusive) list of civil missions whose requirements reasonably match the expected capability of future power systems, and for which a user need can be justified. This section of the report first presents an overview of the mission set and then describes each mission concept in terms of its purpose and objectives, power needs, and design characteristics including alternative means of implementation.

3.1 Civil Mission Set

More than 50 candidate missions were brought to the attention of CMAG through review of NASA in-house and contractor studies, advisory committee recommendations, and recent work within the SP-100 Program. The following criteria were broadly applied to the selection process relevant to the issue of space nuclear reactor application: (1) is the electrical power requirement above some minimum entry level, e.g. 50 kW?, (2) does nuclear power enhance mission performance or its practical implementation?, (3) are the mission objectives supported by established goals for space exploration/application and a clearly identified user community?, and (4) is the mission likely to be implemented in the foreseeable future (1990-2020) on the basis of technology readiness and cost acceptability?

The result of the CMAG selection is a civil mission set comprised of 14 representative applications as listed in Table 1.

The mission set is organized into five classes that best describe the type of application:

1. Manned Orbital Facility - the initial and evolutionary versions of the space station in low Earth orbit.
2. Earth Science and Applications - utility missions serving broad civil sectors in the areas of advanced communications and traffic monitoring/control.
3. Transportation - use of high power electric propulsion systems for payload delivery to geosynchronous orbit and the Moon, and for manned interplanetary flight.
4. Extraterrestrial Resources - processing and utilization of material found on the Moon and near-Earth asteroids.
5. Planetary Exploration - advanced scientific investigation of the small primitive bodies and large outer planets of the solar system.

Table 2 summarizes the key characteristics of the selected mission set in terms of its power utilization function, region of operation, power level, mission duration, nuclear power need, and mission epoch. Entries in the table represent best estimates at this time based on the varied degrees of maturity found in the concept definitions and engineering analyses. The range stated for power requirement reflects this degree of uncertainty, particularly as it relates to ongoing studies of mission design/performance tradeoffs and nuclear power source technology development. Similarly, the mission epoch is not resolved any finer than the expected decade of implementation to reflect uncertainty in technology readiness, mission sequence planning, and development budgets. All missions in the selected set are judged to be enhanced by the availability of nuclear power; in many cases the performance enhancement is very significant and possibly enabling.

An examination of the selected mission set shows that there are ten mission applications which may be significantly enhanced by nuclear power systems. Eight of these missions are likely to be implemented before the

Table 1

CIVIL MISSION SET

- MANNED ORBITAL FACILITY
  - INITIAL SPACE STATION
  - GROWTH SPACE STATION
  - ADVANCED SPACE STATION
- EARTH SCIENCE AND APPLICATIONS
  - GEO COMMUNICATIONS PLATFORM
  - AIR/OCEAN TRAFFIC CONTROL
- TRANSPORTATION
  - GEO PAYLOAD DELIVERY
  - LUNAR PAYLOAD DELIVERY
  - MANNED MARS MISSION
- EXTRATERRESTRIAL RESOURCES
  - LUNAR BASE RESOURCES
  - ASTEROID BASE RESOURCES
- PLANETARY EXPLORATION
  - MULTI-ASTEROID SAMPLE RETURN
  - COMET NUCLEUS SAMPLE RETURN
  - SATURN RING RENDEZVOUS/EXPLORATION
  - FAR OUTER PLANETS ORBITER/PROBES

Table 2

CIVIL MISSION SET - CHARACTERISTICS MATRIX

MISSION	POWER UTILIZATION FUNCTION	REGION OF OPERATION	POWER LEVEL (KW)	MISSION TIME (YRS)	NUCLEAR POWER NEED	MISSION EPOCH
MANNED ORBITAL FACILITY						
INITIAL SPACE STATION	MULTIFUNCTION	LEO	85-200	10	ENHANCING	1990-2000
GROWTH SPACE STATION	MULTIFUNCTION	LEO	300-500	10	SIGNIFICANT	2000-2010
ADVANCED SPACE STATION	MAT. PROCESS	LEO	500-1000	10	SIGNIFICANT	2000-2010
EARTH SCIENCE AND APPLICATIONS						
GEO COMMUNICATIONS PLATFORM	COMMUNICATIONS	GEO	100-200	10	SIGNIFICANT	1990-2000
AIR/OCEAN TRAFFIC CONTROL	OBS. - EARTH	LEO	100-200	10	SIGNIFICANT	2000-2010
TRANSPORTATION						
GEO PAYLOAD DELIVERY	TRANSPORT (EP)	LEO-GEO	100-200	5*	ENHANCING	1990-2000
LUNAR PAYLOAD DELIVERY	TRANSPORT (EP)	LEO-LUNAR	100-200	5*	ENHANCING	2000-2010
MANNED MARS MISSION	TRANSPORT (EP)	IP SPACE	ABOVE 1000	3	SIGNIFICANT	BEYOND 2010
EXTRATERRESTRIAL RESOURCES						
LUNAR BASE RESOURCES	MAT. PROCESS	LUNAR	200-500	10	SIGNIFICANT	2000-2010
ASTEROID BASE RESOURCES	MAT. PROCESS	N.E. SPACE	200-500	5	SIGNIFICANT	BEYOND 2010
PLANETARY EXPLORATION						
MULTI-ASTEROID SAMPLE RETURN	TRANSPORT (EP)	IP SPACE	100-200	8	SIGNIFICANT	2000-2010
COMET NUCLEUS SAMPLE RETURN	TRANSPORT (EP)	IP SPACE	100-200	6	ENHANCING	1990-2000
SATURN RING RENDEZVOUS/EXPLR	TRANSPORT (EP)	IP SPACE	100-200	10	SIGNIFICANT	2000-2010
FAR OUTER PLANETS ORB/PRB	TRANSPORT (EP)	IP SPACE	100-200	10	SIGNIFICANT	1990-2000

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* MULTIPLE SORTIES

year 2010, i.e. representative of the next 25-year planning cycle. A space reactor design in the range 100 to 200 kW of electric power seems quite suitable for the majority of these cases. Two applications in this planning cycle, namely the advanced space station and lunar base resources, would require higher power levels up to 1000 kWe.

3.2 Mission Descriptions

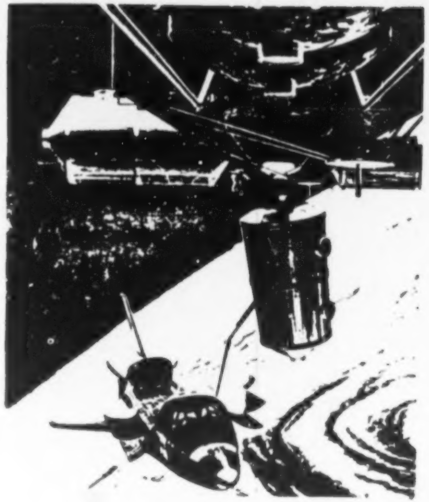
Space Station - Manned Orbital Facility

The current space station concept and its evolutionary versions would host a variety of focused mission applications whose aggregate power demand is very high by present standards. The planned mission set is organized by discipline areas: (1) science and applications, (2) commercial activities, and (3) technology development. Astrophysics, Earth science, and life science comprise the first discipline area and include such missions as Starlab, Lidar Facility, and Life Science Laboratory. Commercial missions include Earth and ocean observations, communications testing, and a variety of materials processing applications such as production of pharmaceuticals, biologicals, crystals, and fibers. Technology development missions address a wide range of space experiments and operations designed to advance component/system technology in such areas as materials performance evaluation, energy conversion research, fluid and thermal physics, and system operations. Figure 4 illustrates the space station concept.

The materials processing missions in particular have high power requirements for both electrical and thermal power. The orbiting space station provides an environment unique for materials processing due to the virtual elimination of gravitational forces, a condition attainable on Earth for only a few seconds at a time. Semiconductor materials, such as gallium arsenide (GaAs), are a vital and pacing item in the development of computer technology. As circuits are more closely packed on a single chip, the effect of impurities and imperfections becomes more significant. Production of the GaAs chip substrate in a minimal-gravity environment eliminates the effects of buoyancy-driven natural convection and allows more fragile containment structures.

Figure 4

SPACE STATION – MANNED ORBITAL FACILITY



- PURPOSE
  - SCIENCE AND APPLICATIONS EXPERIMENTS.
  - COMMERCIAL PRODUCTION.
  - TECHNOLOGY DEVELOPMENT.
  - TRANSPORTATION DEPOT.
- CONCEPT
  - LEO PLACEMENT WITH SHUTTLE SUPPORT.
  - MODULAR DESIGN, GROWTH/CHANGEOUT POTENTIAL.
  - ORBITING PLATFORMS SERVICED BY BASE.
- ENABLING TECHNOLOGIES
  - EFFICIENT, HIGH POWER ENERGY SOURCE.
  - SEMI-CLOSED LONG-TERM LIFE SUPPORT.
  - AUTONOMOUS SYSTEMS.
- POWER USE (INITIAL STATION)
  - MULTI-FUNCTION (85-200 KWE).
  - 45 - 60 % ALLOCATED FOR COMMERCIAL MISSIONS.
- NUCLEAR BENEFITS
  - CONSTANT POWER WITHOUT STORAGE DURING ECLIPSE.
  - IMPROVED FIELD OF VIEW.
  - LOWER ATMOSPHERIC DRAG AND SOLAR RADIATION PRESSURE.
- NUCLEAR CONCERNS
  - RADIATION PROTECTION IN MANNED OPERATIONS.
- KEY PERFORMANCE TRADE
  - REACTOR LOCATION/SHIELDING MASS
    vs RADIATION DOSE AND OPERATIONAL COMPLEXITY.

The conceptual architecture of the space station does not involve a single entity but, rather, the station base and separate orbiting platforms which it supports. However, the dominant power demand is associated with the station base itself and those mission types requiring pressurized module location or attached/external location. Preliminary power budgets have been developed for the (initial) space station mission set through the years 1991-2000. The average daily power requirements for the aggregate set increases steadily from about 85 kWe in 1991 to 200 kWe in the year 2000. Of this total, the distribution of power by discipline area is 45-60% for commercial missions, 5-14% for science and applications missions, 1-6% for technology development missions, and 28-38% for housekeeping functions; the range stated represents annual variations of phased missions over the nine year period.

Growth and advanced station configurations may be anticipated in later years as evolutionary developments from the initial concept. The discipline area in these cases may be more specialized, e.g. a full-scale construction/assembly/staging base or a high-production manufacturing/-processing facility. Power requirements after the year 2000 could reach the level of 300 to 1000 kWe.

Power system options under consideration for the space station include solar photovoltaic, solar thermal-dynamic, and nuclear reactor. The decision to use solar arrays for the initial station configuration is based on technology availability. This does not preclude later changeout to a more capable or volume-efficient power system as power demand grows. A nuclear power source offers significant advantages by virtue of its compact size and simplified operational mode. Key potential benefits include: (1) constant power output without energy storage requirements during solar eclipse periods, (2) improved field of view for pointed experiments, (3) fewer constraints on large structure assembly in close proximity to the station, and (4) easier orbital maintenance due to lower drag forces.

Radiation protection in manned operations is a significant concern that must be addressed by proper engineering design. Three options for reactor system location are being studied in detail:

1. attach to station by structural boom
2. attach to station by tether
3. separate from station on free-flying platform

Each of these options incurrs a mass penalty above the nominal system design mass for unmanned operations, and affects the power system/space station interaction in different ways. The boom-mounted approach is the most straightforward solution but requires the largest increase to total system mass; the reactor would be located 30 to 60 meters from the station with a heavy 4-pi shield providing full hemispherical protection to a relatively safe dose rate of 2 mrem/hr. A tethered reactor would be placed much further from the station (e.g. 3000 meters) with a favorable trade between lower shielding requirements and tether system mass. Electrical power could be carried to the station along the long flexible cable. However, recent studies indicate that a more mass-efficient concept would be to employ fluid hoses carrying water to the reactor and hydrogen/oxygen products back to the station where regenerative fuel cells would be used to develop electrical power. In either case, perhaps the main concerns of a tethered configuration are the effect on the microgravity environment and the need for a continuously active reel control system to minimize tether forces and rotational effects on the space station. The third location option offers a radiation-safe environment without added shielding since the reactor is placed at much greater distance on a co-orbiting platform. Electrical power could be transmitted by microwave beaming; the disadvantage of this method are low transmission efficiency and the requirements for large antennas and very accurate line-of-sight beaming. An alternative approach is the hybrid, reactor/fuel cell system mentioned above; a separate vehicle would be required to transport the fluids between the space station and the co-orbiting reactor platform. In summary, continued engineering and systems analysis of these reactor location options can be expected to identify the best and safest way to link nuclear power capability with manned spaced station requirements.

Geosynchronous Communications Platform

Many new concepts in high data rate communications are being developed that will require a transmitter/repeater located in a geosynchronous Earth orbit (GEO). These concepts include direct broadcast video, closed-circuit teleconferencing, electronic mail transmission, and mobile communications. As these concepts are developed and implemented, the number of satellites in GEO could increase to unmanageable proportions if an individual satellite were dedicated to each communications mission. One approach to eliminating the potential congestion in GEO is to combine the functions of several communications missions on to a single communications platform. Each platform would have a number of antennas, transponders, and signal processing capabilities but would have a common structure, power supply, and attitude control system. This approach offers several enhancements to each communications mission.

The direct broadcast concept is an extension of current communication satellite technology. It would permit terrestrial broadcast stations (T.V. and audio) to transmit to a geosynchronous satellite system which would relay the signals for direct reception by users with small home antennas (perhaps less than 1-meter diameter). Mountainous, rural and remote areas currently having poor or no service would benefit. Besides commercial applications in the U.S., the direct broadcast concept could satisfy future international sound broadcasting needs of the U.S. Government.

Travel by government and industry officials for the purpose of attending conferences has become quite costly in terms of both time and resources. Both government and industry could greatly reduce this burden through the use of advanced teleconferencing. Similar gains in efficiency could be obtained through the use of electronic mail and document transfer. Current ideas for satellite supported teleconferencing envision 1250 identical conference rooms distributed over 100 urban areas of the country. Each room contains a television camera and projector, a laser illuminator, and a stereo sound system. The resulting holograms produce three-dimensional images which can walk, talk, and present data.

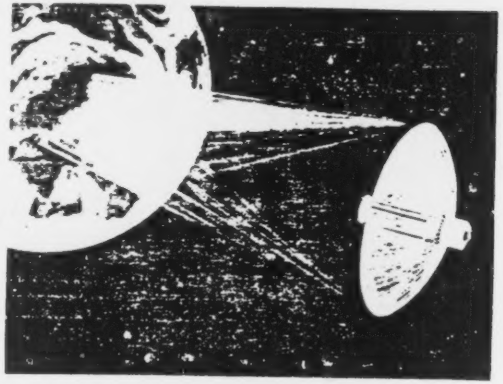
With a variety of functions performed on a single platform, ground antennas need only to point to one satellite in order to be linked to several functions. This is especially beneficial to smaller users who are then able to use a single ground antenna to service a variety of communications functions. If these functions were each performed by dedicated satellites in GEO, such users would either need to reposition their antenna each time a different function was addressed, or make use of dedicated ground antennas for each function. The satellite operators themselves realize a lower operating cost with a multi-function communications platform. Support systems such as power supply, attitude control, thermal management, and structure are provided by the common platform rather than by each communications mission. Using a share of one of these larger-scaled systems not only is of lower cost to the users than their dedicated counterparts, but can be of a higher performance level. A higher-powered transmitter permits using a smaller antenna while retaining the same power-aperature product.

The multi-function communications platform illustrated in Figure 5 requires a large quantity of power for sustained operations. Power requirements for direct broadcast video alone are in the range 50 to 100 kWe, depending on the number of channels and design trades between transmitter power and antenna size. Total requirements for multi-function applications could approach 150 kWe or higher. At such high power levels the usual solar-powered source is not likely to be the best, or perhaps not even a viable design selection. In addition to the high cost factor, the extremely large and flexible solar array structure will place a significant burden on the platform attitude control and antenna pointing systems. Nuclear power enhances the viability of an advanced communications platform by providing lower cost power not only for transmission, but also for stationkeeping and attitude control via an electric propulsion system. The nuclear power source is unaffected by Earth eclipse periods, thus permitting optimal longitudinal locations and elimination of batteries that would otherwise be needed for eclipse operations.

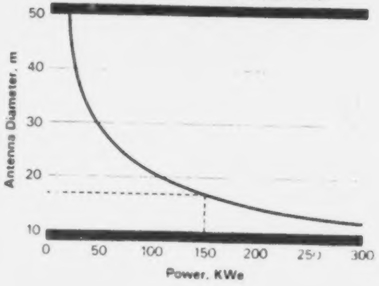
Figure 5

GEO COMMUNICATIONS PLATFORM

- PURPOSE
  - MULTI-FUNCTION TRANSMISSION INCLUDING DIRECT BROADCAST VIDEO, TELECONFERENCING, ELECTRONIC MAIL, AND MOBILE RADIO SUPPORT.
- CONCEPT
  - PLATFORM(S) IN GEOSYNCHRONOUS ORBIT.
  - HIGH POWER, MULTI-BEAM TRANSMISSION.
- ENABLING TECHNOLOGIES
  - MULTI-ELEMENT, LONG-LIFE TRANSMITTERS.
  - LARGE MULTI-BEAM ANTENNA.
  - ADVANCED DATA HANDLING AND SWITCHING.
- POWER USE
  - SIGNAL TRANSMISSION, ORBIT/ATTITUDE CONTROL. (100-200 KWE)
- NUCLEAR BENEFITS
  - LESS EXPENSIVE, HIGH POWER FOR TRANSMITTERS.
  - AUXILIARY POWER FOR ION STATION KEEPING THRUSTERS.
  - UNAFFECTED BY ECLIPSES.
- NUCLEAR CONCERNS
  - ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.
- KEY PERFORMANCE TRADE
  - RF OUTPUT POWER vs ANTENNA SIZE.



Power vs. Antenna Diameter



Air/Ocean Traffic Control

Air traffic patterns within the United States and across its borders are becoming increasingly complex. The North Atlantic corridor, for example, is travelled by aircraft having destinations almost anywhere in the world. Coordination is vital for air safety and reduced delays in takeoff and landing. A high-power, space-based radar system could provide the means for traffic pattern determination and control, including collision-avoidance warning, with little burden on aircraft systems. The radar system would operate in a skin-tracker mode as well as allow options for a low-power transponder (0.5 watt) and small antenna size on-board the aircraft. The mission concept is pictured in Figure 6.

A related application for a space-based radar is a low-cost collision-avoidance system for use by ships and small boats. The concept envisions a time-difference-of-arrival receiver and pulse transponder on each vessel. Pulse trains broadcast by the satellite system would be received and rebroadcast by each vessel. The receiver on each vessel would sound a collision warning if the delay between direct and rebroadcast-received signals approaches zero. A small boat could utilize this system in lieu of an expensive shipboard radar.

Preliminary analysis of a space-based radar system for aircraft traffic control indicates a power requirement in the range 50 to 200 kWe depending on such objective design factors as resolution, orbit altitude, number of targets, range of coverage, and antenna size. Desired resolution limits for locating and tracking commercial aircraft in the North Atlantic corridor are a vertical accuracy of about 75 meters and a horizontal accuracy of at least 500 meters. Information should be updated on a very frequent basis, e.g. every 10 seconds. An extremely large antenna is required for skin-tracking from geosynchronous orbit altitude even when high power is available for signal transmission. Low orbit operation is impractical because of the number of radar platforms that would be needed for continuous coverage. A possible compromise of mid-altitude orbits, which would reduce the number of radar platforms and allow reasonable size antennas, has the problem of natural radiation damage with power output degradation if solar arrays are employed. Nuclear power offers a significant benefit in this regard since operation

Figure 6

AIR/OCEAN TRAFFIC CONTROL

- PURPOSE

  TRAFFIC PATTERN DETERMINATION AND CONTROL.
  COLLISION-AVOIDANCE WARNING FOR AIRCRAFT AND/OR SHIPS.

- CONCEPT

  RADAR PLATFORM(S) IN LEO (700 - 4000 km).
  NORTH ATLANTIC TRACK COVERAGE.
  SKIN TRACKING MODE, SMALL TRANSPONDER ON VESSEL.
  DUAL MODE TRANSMITTER FOR VERTICAL/HORIZONTAL RESOLUTION.

- ENABLING TECHNOLOGIES

  MULTI-BEAM SCANNING ANTENNA.
  HIGH POWER TRANSCEIVER MODULES.

- POWER USE

  RADAR PULSE TRANSMISSION.
  (40-200 KWE)

- NUCLEAR BENEFITS

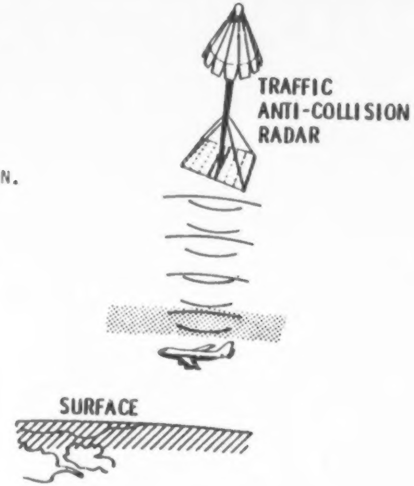
  HIGH POWER ALLOWS SMALLER ANTENNA,
  MORE COVERAGE, HIGHER RESOLUTION.
  ELECTRIC PROPULSION FOR ORBIT/ATTITUDE CONTROL.

- NUCLEAR CONCERNS

  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

- KEY PERFORMANCE TRADE

  POWER LEVEL vs ANTENNA SIZE.



in the radiation belts is possible without power degradation. Additional benefits are that high power availability permits smaller antenna size, broader coverage, higher resolution, and more on-board processing capability. Finally, combining the nuclear power source with an electric propulsion system might further enhance this mission concept by offering efficient long-term propellant utilization for orbit and attitude control.

Geo and Lunar Payload Delivery

The transport objective of this mission class is delivery of large payloads to destinations in Earth-Moon space, primarily to geosynchronous orbit (GEO) and secondarily to the Moon if a lunar base development is initiated by NASA. Recent studies projected to the year 2000 show a ten-to-hundred-fold increase in annual spacecraft mass delivered to GEO. Current capability as represented by the chemical Inertial Upper Stage is limited to about 3000 kg, which is considerably less than desired for many future mission applications. Centaur would double this payload capability but the present stage is costly and not reusable. Planned development of a reusable Orbit Transfer Vehicle (OTV) employing cryogenic propellants and aero-assisted return would probably satisfy most future needs, especially if the OTV system is space-based, i.e. operated in conjunction with a space station serving as a transportation node for refueling and payload integration. For example, a 2-stage aero-OTV (60,000 lb propellant loading, each stage), each stage recoverable, could deliver 20,000 kg to circular orbit conditions at GEO. Alternatively, this vehicle could place 43,000 kg on a transfer trajectory to lunar landing or deliver over 20,000 kg to lunar orbit. The reusability lifetime of these OTV's has been estimated to be about 10 flights with propellant resupply in low Earth orbit.

A nuclear-powered electric propulsion vehicle (NEP) has been studied to ascertain its transportation attributes. A NEP tug would be reusable and, because of its high propellant mass efficiency, there exists the potential for more economical operations than chemical OTV's in high traffic model scenarios, i.e. fewer Shuttle support flights. As shown in Figure 7, the penalty one pays for low thrust flight is long trip times, e.g. several months to GEO rather than several hours. A 100 kWe NEP tug

Figure 7

GEO PAYLOAD DELIVERY

- PURPOSE

  TRANSPORT LARGE PAYLOADS
  TO GEOSYNCHRONOUS ORBIT.

- CONCEPT

  REUSEABLE ORBIT TRANSFER VEHICLE.
  MULTIPLE SORTIES FROM LEO.

- ENABLING TECHNOLOGIES

  ADVANCED CHEMICAL OR
  ELECTRIC PROPULSION SYSTEMS.

- POWER USE

  ELECTRIC PROPULSION (100-300 KWE).

- NUCLEAR BENEFITS

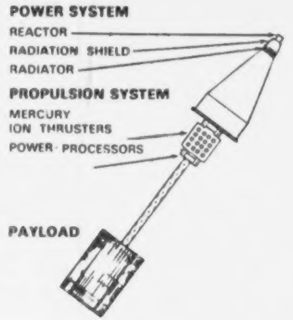
  LARGER PAYLOADS (BUT LONGER TRIP TIME).
  FEWER SHUTTLE LAUNCHES.

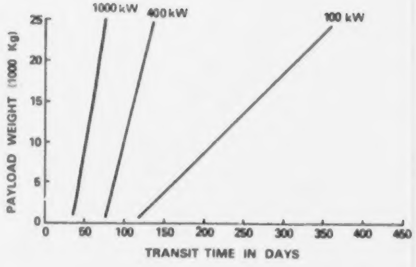
- NUCLEAR CONCERNS

  ADEQUATE SHIELDING AGAINST REACTOR RADIATION.
  LONG EXPOSURE OF PAYLOADS IN VAN ALLEN BELTS.

- KEY PERFORMANCE TRADE

  TRIP TIME vs POWER LEVEL.


POWER SYSTEM
REACTOR
RADIATION SHIELD
RADIATOR
PROPULSION SYSTEM
MERCURY
ION THRUSTERS
POWER PROCESSORS
PAYLOAD



could deliver payloads in the range 7500 to 10,000 kg with a one-way transfer time of 180 days to GEO. At 300 kWe input power, the trip time could be reduced to about 80 days.

Table 3 compares the performance characteristics of all-chemical and NEP transport options for GEO payload delivery. The scenario assumed here is that 1200 metric tons must be delivered to GEO over a 5-year period. Both propellant and payload are initially brought from Earth, but the delivery operations are otherwise based from low orbit. Two chemical transport cases are examined: a 2-stage large OTV configuration with each stage carrying 60,000 lbm of cryogenic propellant, and a single stage small OTV having a 38,000 lbm propellant capacity. A similar range of NEP transport capability is described by the 1000 kWe and 120 kWe systems. Although the NEP round-trip times are quite long compared to chemical OTV delivery, the payload per sortie is twice as large and hence the total number of sorties is halved. More importantly, fewer than half the number of Shuttle launches are required for NEP payload delivery with the direct result that estimated transportation cost is reduced significantly. Another potential benefit, depending on one's point of view, is the savings of more than 3000 metric tons of liquid hydrogen and oxygen that would have been used by the OTV transports.

In another analysis of NEP transport capabilities, the focus was on comparison of low-base (700 km altitude) and high-base (16,000 km altitude) operations for GEO, lunar and interplanetary missions. The NEP vehicle makes multiple round trips to its base altitude (where it is refueled) until its rated lifetime is reached. While the low-base operation could be supported by Shuttle, chemical OTV's were envisioned for support of high-base operations. The NEP system assumed for this scenario had a power rating of 120 kWe, individual thruster lifetime of 20,000 hrs but increased effectively to 40,000 hrs through redundancy, and a system dry mass (power and thrust subsystems) of 4800 kg. Performance results for GEO missions from low-base showed a per trip payload capability of 12,000 kg, a round-trip time of 416 days, and 4 sorties within the lifetime constraint. High-base operation for GEO missions allowed 7000 kg payload per trip, a round-trip time of 80 days, and a 20-sortie lifetime. In one example scenario, a fleet of 5 NEP transports (3 dedicated to

Table 3

GEO PAYLOAD DELIVERY - 1200 METRIC TONS OVER 5 YEARS

SPACE-BASED OPERATIONS PAYLOAD AND PROPELLANT FROM EARTH	ALL-CHEMICAL		NUCLEAR ELECTRIC PROPULSION	
	OTV-2L	OTV-1S	NEP (1000 KW)	NEP (120 KW)
PAYLOAD/SORTIE (MT)	20	6	40	12
ROUND TRIP/SORTIE (DAYS)	2	2	174	420
NUMBER OF SORTIES	60	200	30	100
NUMBER OF OTV TRANSPORTS(1)	6	20	—	—
NUMBER OF NEP TRANSPORTS(2)	—	—	3	25
NUMBER OF SHUTTLE LAUNCHES	155	174	65	68
TOTAL OTV LH_2/LO_2 (MT)	3265	3450	—	—
TOTAL NEP PROPELLANT (MT)	—	—	625	375
TRANSPORTATION COST(3) (FY84 $B)	16	18	8	12

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(1) OTV LIFETIME = 10 SORTIES
(2) NEP LIFETIME = 5 YEARS
(3) DOMINATED BY SHUTTLE COSTS AT 0.1B/LAUNCH

planetary missions before GEO service) operating from high-base delivered 350 metric tons to GEO in 50 sorties, 43 metric tons to lunar orbit in 7 sorties, and 8.5 metric tons on 4 planetary missions.

Manned Mars Mission

Mars is a key planetary body in the scheme of solar system exploration. Through a process of initial flyby reconnaissance and subsequent orbiter and lander explorations it has become apparent that this is the most Earth-like planet in our solar system. Hence, Mars is an important element of comparative planetology, a process by which we hope to better understand the Earth's origin and evolution. Continuing this process is expected to require future missions of intensive study which will produce detailed geochemical surface maps, a better understanding of Mars climate (including the important phenomenon of volatile transport and exchange), and eventually returned samples of Mars for detailed Earth studies. This progression of exploration activities will initiate for us a transition from Mars exploration to utilization, with emphasis on habitation because of the planet's Earth-like characteristics. As this transition approaches, the decision to initiate manned missions to the planet becomes increasingly imperative. Underlying such a decision is the fundamental presumption that our society will continue to accept the challenge of its expanding frontiers, eventually exporting itself from the surface of our planet.

The mission addressed in this summary is assumed to be the first manned Mars mission. Its most important objective would be to determine, construct, and verify the necessary building blocks for sustaining manned access to Mars. Given this guideline, it would, nonetheless, also be an excellent opportunity to expand exploration activities, particularily on the surface of Mars. Mission capabilities which are candidate objectives for this initiative include bulk sample return, detailed local exploration, basing confirmation, automated surface laboratory set-up, and delivery of base equipment, to name several. While the specific objectives for this first manned expedition to Mars will continue to evolve with current exploration in particular and Earth-orbital manned activity in general, there can be no doubt that this mission will contain a rich complement of objectives to advance our understanding and conquest of the solar system.

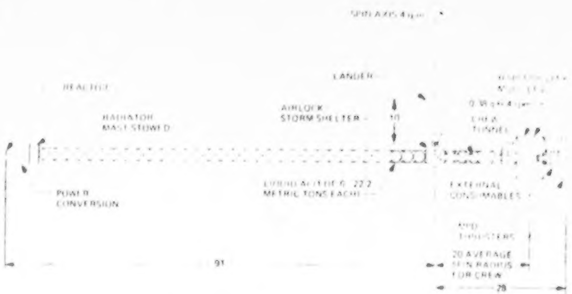
As shown in Figure 8, one mission concept for this endeavor is characterized by a single nuclear-powered spacecraft with an attached lander. A crew of five persons would cruise to Mars in approximately 600 days. A period of 100 days at Mars would be permitted for reconnaissance and exploration. During this time the lander would take three crew members to the surface of the planet for detailed investigations, and basing activities as appropriate to the expedition's objectives. A shorter return trip of about 270 days would complete the mission within a total duration of almost 32 months (2.6 years). The spacecraft would be in powered micro-gravity mode for approximately half of this time. During the remaining coast period an artificial gravity of about 0.4 g's could be induced through vehicle rotation (@ 4 rpm). The total mass in low-Earth orbit to undertake the mission is estimated to be 344 metric tons which is equivalent to about 12 STS loads. Significant elements of the nuclear electric propulsion system required for this concept include a 6 MWe nuclear reactor, magneto-plasma-dynamics (MPD) thrusters, and a liquid droplet radiator operating as the thermal sink. The system would operate with argon propellant with a maximum jet power of 3 MWe.

A brief literature survey indicates that the most competitive all-chemical alternative concept for a manned Mars mission would require at least 21 STS loads to assemble in LEO. Mission time would be somewhat shorter at 2.0 years, but staytime would be reduced to as little as 30 days and a required Venus swingby would bring the manned spacecraft to within 0.5 AU of the Sun increasing the hazard of a solar flare by as much as a factor of four. Other non-nuclear options, generally requiring both more mass and more time, include all-chemical direct missions and hybrid chemical/SEP direct missions. The described nuclear-electric propulsion concept holds the advantages of: 1) comparatively short trip time with adequate staytime; 2) minimum number of autonomous systems; and 3) relative performance insensitivity to concept growth.

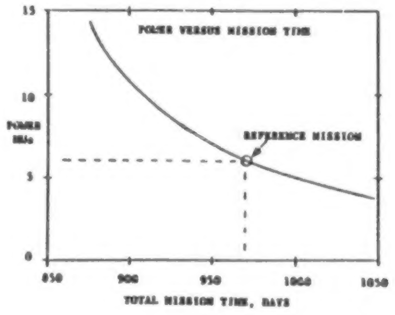
Figure 8

MANNED MARS MISSION

- PURPOSE
  - DETERMINE, CONSTRUCT, AND VERIFY BUILDING BLOCKS NECESSARY FOR ACCESS TO MARS.
  - EXPLORE SURFACE OF MARS.
- CONCEPT
  - 5 MEMBER CREW.
  - 2.6 YEAR MISSION TIME.
  - 100 DAYS AT MARS WITH 30 DAYS ON SURFACE.
- ENABLING TECHNOLOGIES
  - FBR REACTOR.
  - DYNAMIC CONVERSION.
  - LIQUID DROPLET RADIATOR.
  - MAGNETOPLASMA DYNAMIC THRUSTER.
  - CLOSED AIR AND WATER LIFE SUPPORT.
- POWER USE
  - PROPULSION (6 MWE).
- NUCLEAR BENEFITS
  - COMPARATIVELY SHORT TRIP TIME WITH ADEQUATE STAY TIME.
  - MINIMUM NUMBER OF AUTONOMOUS SYSTEMS.
  - RELATIVE PERFORMANCE INSENSITIVE TO CONCEPT GROWTH.
- NUCLEAR CONCERNS
  - RADIATION PROTECTION OF CREW.
  - LARGE DEVELOPMENT EFFORT FOR ENABLING TECHNOLOGY.
- KEY PERFORMANCE TRADE
  - TRIP TIME vs POWER LEVEL.


SPIN AXIS 4 rpm
REACTOR
LANDER
RADIATOR
MAST STOWED
AIRLOCK
STORM SHELTER
10
0.38 g at 4 rpm
CREW
TUNNEL
POWER
CONVERSION
METRIC TONS EACH
EXTERNAL
CONSUMABLES
MPD
THRUSTERS
91
20 AVERAGE
SPIN RADIUS
FOR CREW
28

APPROXIMATE DIMENSIONS IN METERS



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Lunar Base Resources

Preliminary studies have indicated that the use of certain nonterrestrial resources may be commercially advantageous within two decades. Oxygen from the Moon appears to be the most likely candidate for an initial space-resource product. The processed liquid oxygen would be used for propellant for orbit transfer vehicles (OTV's) carrying cargo from low Earth orbit (LEO) to geostationary orbit (GEO) and other destinations. The benefit from this seemingly indirect source derives from the fact that 7 times less energy is required to go from the Moon to LEO then to go from the Earth's surface to LEO. Since about 60% of the gross mass of an OTV is made up of liquid oxygen (burned with liquid hydrogen fuel), transporting oxygen from the Moon rather than from Earth may result in significant cost savings for high traffic scenarios. Further advantages would accrue if a source of hydrogen could be found along with oxygen in accessible quantities, e.g. water ice at the lunar poles. Besides propulsion, another important use of lunar materials would be in the construction and radiation shielding of a manned lunar base. This mission application is illustrated in Figure 9.

Research has been underway for several years on extraterrestrial materials utilization including the various operational steps of mining, beneficiation, refining, processing, fabrication, and transportation, and the energy system requirements associated with these operations. Analytical and experimental work has been carried out for several types of primary processes such as magma electrolysis and vapor phase reduction. Process temperature requirements are in the range 1500-2000 K for electrolysis and 2500-3000 K for vapor separation. Both processes are likely to produce, in addition to oxygen, metal mixtures which will require further processing into useful metal products. Vacuum distillation methods have been identified as effective for separation of products such as aluminum, silicon, magnesium, calcium, and titanium. Silicate processing is another research area in which analytical and experimental work has focused on fabricating useful shapes from mixed lunar oxide powders. Characteristic properties have been determined as a function of compaction, process temperature, and cooling rate.

Figure 9

LUNAR BASE RESOURCES

- PURPOSE
  PROCESS LUNAR SOIL FOR LO_2 AND OTHER PRODUCTS.

- CONCEPT
  MAN-OPERATED LUNAR BASE.

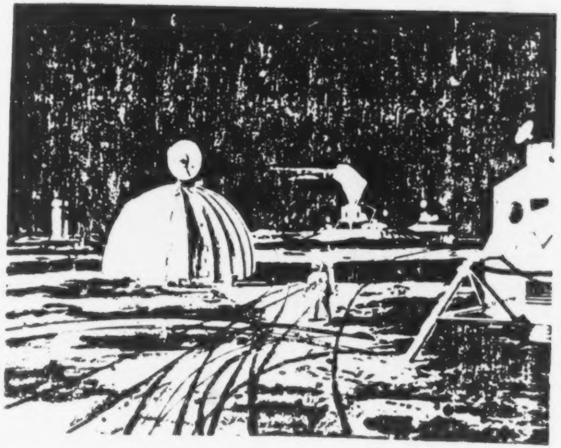
- ENABLING TECHNOLOGIES
  IMPROVED PROCESSING EFFICIENCY.
  ADVANCED POWER SOURCE (THERMAL/ELECTRICAL).
  EFFICIENT BULK TRANSPORTATION.

- POWER USE
  PROCESSING OPERATIONS, LIFE SUPPORT.
  (200-500 KWE)

- NUCLEAR BENEFITS
  ECONOMIES OF SCALE AT HIGH POWER LEVELS.
  NO SOLAR DEPENDENCE - 100% DUTY CYCLE.
  BASE SETUP SIMPLICITY.
  SOURCE OF BOTH THERMAL AND ELECTRICAL POWER.

- NUCLEAR CONCERNS
  RADIATION PROTECTION IN MANNED OPERATIONS.

- KEY PERFORMANCE TRADE
  PRODUCTION RATE vs POWER REQUIREMENT.



Resource utilization operations will require energy in both thermal and electrical form. Thermal energy may be obtained directly from the Sun or from a nuclear heat source. Electrical power could be converted from the basic heat source (solar thermal collector or nuclear reactor), chemical fuel cells, or obtained directly from photovoltaic arrays. The amount and form of the energy required, conversion efficiency, and mass of the power supply are crucial parameters in selecting the best energy system. Primary processing is by far the largest energy user among the various operations. Electrolysis and vapor phase processing are estimated to require total energies of 10-30 MW-hr and 50-100 MW-hr per metric ton of output, respectively, with an electrical/thermal energy ratio of about 10. The minimum production rate of lunar oxygen which is assumed to be required for a commercially viable facility is of the order 100 tons/year. This implies power levels of between 100 and 1000 kWe with possible growth to several megawatts for an advanced processing facility. Nuclear reactor power is, at the very least, an enhancing option for a lunar resource base. Besides the potential economy of scale at very high power levels, the nuclear option would allow a 100% duty cycle compared to photovoltaic power which cannot be operated during the two-week lunar dark period each month.

In the broadest sense, lunar base objectives would: (1) demonstrate peaceful uses of U.S. technology; (2) establish a modest, expandable human settlement off Earth; (3) conduct scientific investigations in the planetary and astrophysics areas, and; (4) evaluate the economic potential of lunar resources. One lunar base scenario would evolve along the following timeline: unmanned orbital and surface exploration program (1990-2000); scientific research base (2000-2005); lunar resource pilot plant and engineering research station (2000-2010); and full-scale production/-manufacturing base (2010-2020).

Asteroid Base Resources

Asteroids in near-Earth space are an alternative, potential source of strategic and economically valuable materials for space applications. Beneficial products include water from hydrous silicates, ferrous metals, and platinum-group metals. One reason for the interest in asteroidal resources derives from the fact that it requires less energy to transport materials from some asteroids to LEO than from the Moon to LEO. The key factors in this regard are the special orbit characteristics leading to low-energy accessibility, and the discovery of a sufficient number of such asteroids that allow target selection flexibility over a wide range of launch opportunities. The existence of Earth-Trojan asteroids, speculated but as yet undiscovered, could be very important in this regard.

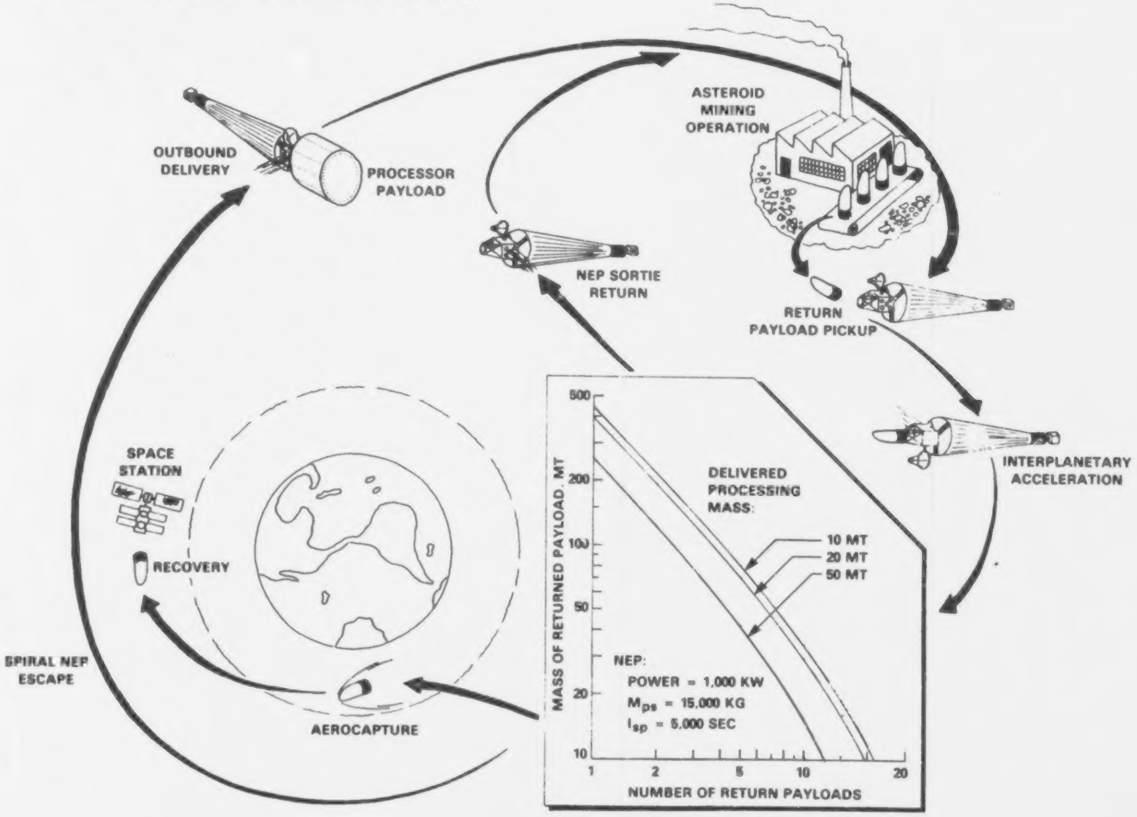
The gaseous carbonyl process, which has been used extensively for the production of nickel on Earth, appears to be well-suited for the extraction and purification of iron, nickel, cobalt, and precious metals from the free iron thought to be available in many asteroids. Theoretical design of metal extraction processes has already begun. While the process appears to be relatively simple with modest power requirements, the reactant carbon monoxide must either be brought from Earth or manufactured at the processing site. One of the major uncertainties at present concerns the physical properties of asteroid surface materials. Engineering data on crushing strength, particle size distribution, and other relevant factors will almost certainly necessitate in situ study by precursor spacecraft/lander missions. Additional early work needs to be done on magnetic separation techniques and the effect of dust on the seals needed to maintain internal pressure during the carbonyl extraction process.

One may envision three plausible scenarios for implementing the utilization of asteroid resources. In the first case, an asteroid return "truck" simply goes to the target, picks up large quantities of dirt and rocks, and returns this payload for subsequent processing in a low Earth orbit facility. The second scenario involves material crushing and magnetic separation by the asteroid lander with the final processing steps taking place at the Earth space station. Finally, a sufficiently capable asteroid mining base could carry out all necessary functions including processing, returning only the refined products to Earth.

The advantage of nuclear power for this mission apply to transportation as well as asteroid mining and processing operations. Figure 10 illustrates a possible nuclear electric propulsion (NEP) transport concept and describes the tradeoff between return payload quantity and number of mission sorties. In this scheme the NEP vehicle is employed first to

Figure 10

ASTEROID RESOURCES: NEP TRANSPORT CONCEPT


OUTBOUND DELIVERY
PROCESSOR PAYLOAD
ASTEROID MINING OPERATION
NEP SORTIE RETURN
RETURN PAYLOAD PICKUP
INTERPLANETARY ACCELERATION
SPACE STATION
RECOVERY
SPIRAL NEP ESCAPE
AEROCAPTURE
MASS OF RETURNED PAYLOAD, MT
500
200
100
50
20
10
1
2
5
10
20
NUMBER OF RETURN PAYLOADS
DELIVERED PROCESSING MASS:
10 MT
20 MT
50 MT
NEP:
POWER = 1,000 KW
M_{ps} = 15,000 KG
I_{sp} = 5,000 SEC

deliver the asteroid base equipment, a set of aerocapture support systems for payload return, and a propellant supply for its own subsequent use. As payloads are processed and packaged on the asteroid, they are picked up by the NEP which provides a sufficient acceleration to place this payload on a ballistic, Earth-encounter trajectory. The NEP vehicle then separates the payload and returns to the asteroid for another payload pickup. The payloads are recovered in low Earth orbit after aerocapture by the atmosphere. Note that the asteroid material itself provides the bulk and shape of the aerocapture vehicle; the supporting systems carried originally from Earth provide the necessary flight control and integrating structure. As an example design point, a 1000 kWe NEP system delivers 20 metric tons of processing equipment and subsequently returns 30 metric ton payloads on each of 10 mission sorties. Additional NEP fleet vehicles could be sent to the asteroid to continue the payload return throughput.

To summarize, asteroid base objectives combine scientific investigations and development of an alternative source for materials needed in advanced space applications. A possible scenario would be: ground and space telescope search to characterize near-Earth asteroids including a possible Earth-Trojan population (1985-2000); unmanned reconnaissance missions to near-Earth asteroids (1995-2005); unmanned and possibly manned missions involving intensive exploration of selected targets for resource utilization (2000-2010); and development of asteroid materials processing base (2005-2020).

Multi-Asteroid Sample Return

The asteroids comprise a numerous and diverse population of small bodies in the solar system, distributed mainly in the spatial region between Mars and Jupiter. Scientific interest in asteroids is heightened by the expectation that these relatively primitive bodies hold important clues to the physical and chemical processes associated with the early development and evolution of the solar system. First generation missions are being planned as a component of the SSEC*-recommended Core Program for planetary exploration. Such missions will provide rendezvous/orbiter science capability for several selected asteroid targets in the main belt and in near-Earth space. Depending on data return from this asteroid exploration initiative, and on the availability of advanced propulsion systems, there could be considerable interest in returning samples from one or, preferably, several asteroids. The information obtained in Earth-based laboratories would be of scientific value in itself, but may also support future programs in extraterrestrial resource utilization.

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* Solar System Exploration Committee of the NASA Advisory Council.

The science value of sample return may be greatest if the material is not previously known as a meteorite type. Carbonaceous chondrites, which are the most primitive, most studied type of meteorite, are very rare in meteorite collections, presumably because of their fragility and destruction during atmospheric entry. A sample return mission should include a C-type asteroid target, preferably one on which bound water has been detected. Some issues which can only be resolved by the study of returned samples of carbonaceous chondrites include: water content, state of hydration, indigeonous organic compounds, and improved knowledge of solar system abundance values for certain chemical elements. Other types of studies that are best carried out on samples rather than being made in situ include: mineralogy and petrography, shock and irradiation effects, age dating, stable isotope measurements, identification of organic chemicals, and radioactivity.

A minimum mass of several kilograms seems to be adequate for each target sampled. Of greater concern is to assure that the sample is representative of the object being sampled. This could be accomplished if the orbiting spacecraft and the lander include a complement of science experiments in addition to the sample collecting systems. Minimal information about the sample's environment can be gathered by imaging, global chemistry characterization provided by X-ray and gamma-ray spectroscopy, global geophysics including density and gravity field data, and in situ surface chemistry provided by alpha backscatter and X-ray fluorescense. It may also be desired to sample several sites on the same target.

In the proposed mission concept (see Figure 11), the space vehicle system would rendezvous with several (nominally 3) asteroids in succession, staying at least 2 months at each target while performing global science coverage, site selection and characterization, and sample collection operations. A separable, reuseable lander/ascent/rendezvous vehicle collects and returns the samples to the low-thrust transport orbiting the asteroid. Both solar electric (SEP) and nuclear electric propulsion (NEP) would enable this mission - the ballistic flight mode using chemical propulsion is not practical since the velocity impulse requirement exceeds 10 km/sec. With low-thrust propulsion, flight times along each of the trajectory segments between asteroid targets lie in the range of 600 to 800 days. The SEP system design requires a 60 kWe solar array with 4:1 array concentration. A NEP transport with power rating of 100 to 150 kWe offers better performance in terms of larger payload mass, shorter trip time, and/or greater flexibility in target selection. A typical mission shown in Figure 11 could return samples from three asteroids with a round trip time of about 8 years or from four asteroids in 10 years.

Comet Nucleus Sample Return

The primary objective of this mission is to collect a sample of undisturbed comet material from beneath the surface of an active comet, and return it to the Earth in a minimally altered state. Secondary objectives are to characterize the comet to a level consistent with a rendezvous mission and, as an option, monitor comet dynamics through perihelion and aphelion with a long-lived lander/station. The comet nucleus sample return mission has been recommended as an augmentation to the SSEC Core Program for planetary exploration.

The proposed mission consists of several elements. The spacecraft bus would carry a science payload to perform the nucleus characterization and site documentation objectives, and would provide relay control and communication during the sampling process. Two sample devices are specified to collect two 1-meter cores of the nucleus. These are to be separately deployed from the spacecraft and recovered through an automated rendezvous and docking procedure (see Figure 12). The second sampler

Figure 11

MULTI-ASTEROID SAMPLE RETURN

- PURPOSE

  RETURN SURFACE SAMPLES FROM SEVERAL ASTEROIDS.
  SUPPORTING SCIENCE BY ORBITER/LANDER.
  EVALUATE RESOURCE UTILIZATION POTENTIAL.

- CONCEPT

  RENDEZVOUS WITH 3 OR 4 ASTEROIDS.
  60-DAY STAY AT EACH TARGET.
  SAMPLE ACQUISITION BY REUSEABLE LANDER.

- ENABLING TECHNOLOGIES

  ELECTRIC PROPULSION (SEP, NEP).
  AUTOMATED RENDEZVOUS/DOCKING.

- POWER USE

  SEP - 60 KWE ARRAY W/CONCENTRATORS.
  NEP - 100 KWE.

- NUCLEAR BENEFITS

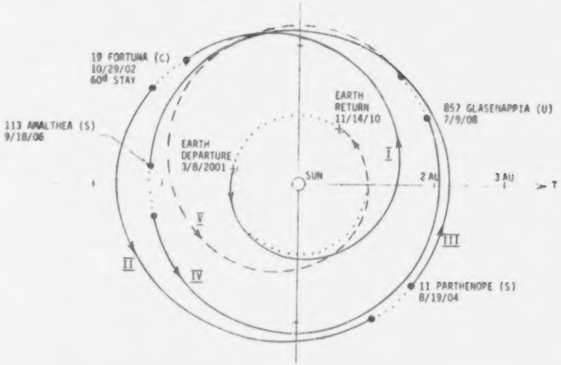
  LARGER PAYLOAD MARGIN.
  SHORTER TRIP TIME.
  TARGET SELECTION FLEXIBILITY.

- NUCLEAR CONCERNS

  RADIATION AND THERMAL SHIELDING OF PAYLOAD.

- KEY PERFORMANCE TRADE

  NUMBER OF TARGETS/TRIP TIME vs POWER LEVEL.


19 FORTUNA (C)
10/29/02
60d STAY
113 AMALTHEA (S)
9/18/06
EARTH
DEPARTURE
3/8/2001
EARTH
RETURN
11/14/10
857 GLASENAPPIA (U)
7/9/08
SUN
2 AU
3 AU
T
I
II
III
IV
V
11 PARTHENOPE (S)
8/19/04

ASTEROID MULTIPLE SAMPLE RETURN PROFILE - ION DRIVE FLIGHT MODE would carry with it a long-lived lander that would be anchored to the comet's surface upon impact. The lander would be capable of monitoring nucleus surface activity over one orbital period of the comet or at least through perihelion and aphelion passages. After recovery by the spacecraft, the core samples would be hermetically sealed in an environmentally controlled capsule to prevent thermal, chemical or radiation contamination during the return trip to Earth. The samples would be returned to a circular, Shuttle-compatible orbit to insure the probability of quick recovery. A space station can play an important role in recovery operations and initial testing of the sample capsule contents.

Potential targets for the comet nucleus sample return mission include all the short-period comets being considered for an earlier rendezvous mission. Emphasis has been placed, however, on the comets Encke, Tempel 2 and Wild 2. These three comets, in addition to satisfying the established criteria of good rendezvous targets, have perihelion passages occurring shortly after the turn of the century thus providing opportunities for launch prior to the year 2000 but still allowing time for data to be returned from a possible precursor rendezvous mission. Depending upon the propulsion system and flight mode selected, launch opportunities for near-perihelion encounters with at least one of these comets exist every year from 1997 to 2002.

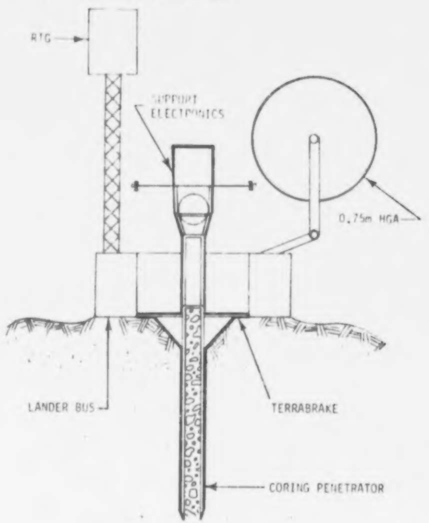
Potential flight modes for mass delivery include ballistic/chemical propulsion, solar electric propulsion (SEP), and nuclear electric propulsion (NEP). Ballistic opportunities are more limited in comet selection, have long round-trip times, and generally require several advanced technologies including on-orbit assembly of Centaur stages and space storable retropropulsion. SEP is an enabling technology for all comet sample return missions providing that comet rendezvous occurs in the vicinity of perihleion; round-trip times are 5 to 6 years and a single Shuttle/Centaur launch is sufficient. The availability of NEP transportation enhances the mission opportunities through its higher payload performance. NEP permits greater mission design flexibility by providing a wider range of encounter time thus reducing hazards due to comet dust activity near perihelion. Shorter trip times may also be possible. The large amount of electric power available from the nuclear reactor source

Figure 12

COMET NUCLEUS SAMPLE RETURN

- PURPOSE
  - OBTAIN PRISTINE SAMPLE OF COMET NUCLEUS.
  - MONITOR COMET DYNAMICS VIA LONG-LIVED LANDER.
- CONCEPT
  - RENDEZVOUS WITH SHORT-PERIOD COMET.
  - CONDUCT SITE SURVEILLANCE/DOCUMENTATION.
  - COLLECT 1-METER CORE SAMPLES FROM 2 SITES.
  - LEAVE MONITORING STATION ON SURFACE.
- ENABLING TECHNOLOGIES
  - ELECTRIC PROPULSION (SEP,NEP)
  - AUTOMATED RENDEZVOUS/DOCKING.
- POWER USE
  - SEP-36 KWE ARRAY W/CONCENTRATORS.
  - NEP - 100 KWE.
- NUCLEAR BENEFITS
  - EARLY ENCOUNTER-REDUCED DUST HAZARD.
  - LARGE PAYLOAD MARGIN.
  - SHORTER TRIP TIME.
- NUCLEAR CONCERNS
  - RADIATION AND THERMAL SHIELDING OF PAYLOAD
- KEY PERFORMANCE TRADE
  - TARGET COMET SELECTION.
  - SEP vs NEP FLIGHT MODE.

PENETRATOR SAMPLER/LANDER



is not absolutely necessary for the science experiments and sampling process, but could be viewed as an enhancing option.

Saturn Ring Rendezvous/Exploration

Important science questions have been raised by the spectacular observations of Saturn's rings by the Voyager spacecraft. The origin and evolution of the rings as relating to processes at work in the Saturn/satellite system is of great interest. A follow-on Saturn orbiter mission with capabilities similar to Galileo will provide long duration, remote observations which should yield a better characterization of ring structures, dynamics and possible satellite interaction. However, many questions dealing with origin and processes of ring formation and the nature of ring particles will likely remain unresolved until it is possible to perform close-up (in situ) experiments.

The primary objectives of this advanced mission to rendezvous with Saturn's rings are to conduct detailed observations of individual ring particles and in situ composition measurements of the particles and their immediate environment. This will require spacecraft systems with enormous propulsive capability. Chemical propulsion systems are not adequate to attain near-circular orbits even at the outer edge of the ring system. This mission requires a high performance low-thrust system which, at Saturn's distance from the Sun, is enabled only by a nuclear power source. Given the large mass delivery potential of nuclear electric propulsion, it becomes reasonable to consider other important science objectives which can be achieved enroute to ring rendezvous. These secondary objectives comprise an extended exploration of the Saturn system and might include such options as atmospheric entry probes, a Titan orbiter, Titan buoyant station and/or lander, close investigation of the other satellites, global studies of Saturn's atmosphere, and a spatial/temporal investigation of the system of fields and particles.

This mission concept employs a nuclear-powered electric propulsion system that transports the payload from Earth to Saturn in about eight years. Upon reaching the vicinity of Saturn, the vehicle then spirals inward along continuously decreasing circular orbits in the equatorial plane. The orbit of Titan is reached in about 100 days. Depending on possible mass dropoff at Titan, an additional 1.5 to 2 years is required to spiral in to a circular orbit at the distance of the inner D ring (1.1 Saturn radii). When the vicinity of the outer G ring is reached, the thrusting profile is modified to keep the spacecraft in a non-Keplerian minor-circle orbit just above or below the ring plane. The spacecraft thus skims across the rings toward Saturn, like the stylus of a phonograph gliding across a record, making detailed observations of each ringlet from a very close distance. At intervals during this orbital process, thrust could be terminated for a few hours causing vertical motion toward the rings or through low density gaps. Alternatively, a tethered science package might be lowered into the ring plane for in situ measurements.

Performance of this mission as shown in Figure 13 requires an electric power from the reactor/power conversion system in the range 100-150 kW. This assumes a 1500 kg mission module, a power/propulsion system dry mass in the range 5000-6000 kg, and a maximum mission duration of 10 years. To illustrate the mission time vs power tradeoff, at 5000 kg dry mass the mission time is reduced from 10 years to 7 years as power increases from 100 to 150 kWe. At 6000 kg dry mass, the 10-year maximum requires a power level of 120 kWe whereas a 150 kWe system could accomplish the mission in 8 years.

Far Outer Planets Orbiter/Probes

The SSEC-recommended Core Program for planetary exploration includes a Uranus flyby/probe mission to continue the reconnaissance of Uranus beyond Voyager. Neptune and Pluto are also considered high priority targets, but missions were thought to be impractical during this century due to scheduling and technology limitations. However, as a potential augmentation option, an integrated and comprehensive program of scientific exploration of the far outer planets with orbiters and atmospheric probes can be enabled by advanced propulsion technology such as nuclear electric propulsion. The program is comprised of three individual missions: Uranus orbiter/probe, Neptune orbiter/probe, and Pluto orbiter. Fast flight time to these targets is a key aspect here - it is desired that no mission exceed 12 years duration.

Figure 13

SATURN RING RENDEZVOUS/EXPLORATION

- PURPOSE

  DETAILED INVESTIGATION OF RING STRUCTURE/COMPOSITION.
  EXTENDED OBSERVATION OF SATURN AND TITAN.

- CONCEPT

  SPIRAL IN PAST TITAN-PAYLOAD DROPOFF.
  CONTINUE SPIRAL TO INNER D-RING.
  MAINTAIN 1-20 km DISTANCE ABOVE RING PLANE.

- ENABLING TECHNOLOGIES

  ELECTRICAL PROPULSION.

- POWER USE

  PROPULSION (100-200 KWE).

- NUCLEAR BENEFITS

  ENABLES MISSION (NO NEAR-TERM ALTERNATIVE).
  LARGE PAYLOAD CAPABILITY.

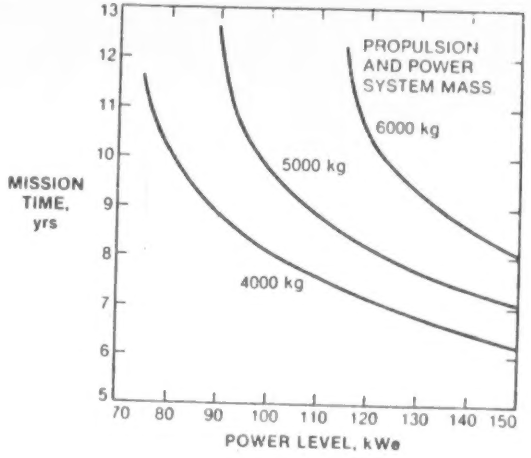
- NUCLEAR CONCERNS

  POSSIBLE INTERFERENCE WITH SCIENCE MEASUREMENTS.
  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

- KEY PERFORMANCE TRADE

  TRIP TIME/PAYLOAD vs POWER LEVEL.

- SP-100 NUCLEAR POWER SOURCE
- 1500 kg (S/C AND SCIENCE) PAYLOAD
- 2 yr SPIRAL FROM TITAN ORBIT TO 1.1 R_S



Scientific objectives for exploration of these planets may be categorized in six areas of investigation: (1) atmospheres, (2) interiors, (3) surfaces of Pluto and satellites, (4) ring system, (5) magnetospheres, and (6) solar wind interaction. Uranus and Neptune have deep, hydrogen-dominated atmospheres. A successful Voyager 2 extended mission will give the rotation rate and axis and preliminary atmospheric properties above the clouds (i.e., structure, circulation patterns, wind speeds and composition) at a single point in time. The advanced exploration missions can improve our knowledge of the above by extending the interval of measurements using synoptic coverage. This also provides information about the dynamic behavior of the atmosphere including seasonal changes. Better data are obtained because the orbiter is able to work in an adaptive mode; that is, modifying its data acquisition patterns in response to prior discoveries. A very important objective for an exploration program is to measure the atmospheric properties above, in and below the cloud layer. The H/He ratio is of particular interest. The objective is satisfied in part with an atmospheric probe that is also able to provide "ground-truth" data above the clouds for calibrating the orbiter's remote sensing instruments.

The mass, higher order gravity field coefficients, radius, shape and excess thermal emission are essential data for modeling the interiors of planetary bodies. Among the goals of the proposed orbiter missions should be long-term observations of the planets and encounter of as many satellites as possible at close range where accurate photometric and radiometric tracking data can be acquired. This data can be used to derive the bulk density for a body and to infer its composition and internal structure. For Pluto and its large satellite Charon, and the satellites of Uranus and Neptune, the surfaces reveal important clues regarding the origin and evolution of these bodies. An important orbiter mission objective is to characterize the surface properties, i.e., morphology, composition, and physical state. Finally, the extended observation time and spatial coverage provided by a Uranus and Neptune orbiter would greatly enhance the science potential of particle and field experiments relevant to magnetosphere and ring investigations.

In the example design concept, initial elliptical orbits would be established at Uranus and Neptune for purposes of science observations over a large range of distances from the planet. The atmospheric entry probe could be released from orbit, or alternatively, on approach to the planet. In the case of Neptune, the initial orbit would allow close encounter with Triton which is massive enough to assist in orbit capture and provide significant orbit change through repeated gravity-assist encounters. At Pluto, a circular orbit at about ten planet radii would place the spacecraft into near-rendezvous conditions with its satellite Charon. Subsequent maneuvering, made easy by Pluto's small gravitational field, would allow close-range investigation of both bodies and the spatial regions between them.

There are only two advanced technologies that can enable this far outer planet exploration program within a 12-year trip time constraint -- aerocapture and nuclear electric propulsion (NEP). Aerocapture can be employed only at Uranus and Neptune. Ballistic flights with aerocapture need to be combined with on-orbit assembly of injection stages (e.g. two stacked Centaurs), and also with Jupiter swingby in the case of Neptune. In contrast, a NEP system with commonality in design enables all three missions. Spiral escape from low Earth orbit can be employed in lieu of Centaur stages thereby requiring only a single Shuttle launch. Launch can occur any year since the infrequent Jupiter swingby opportunities are not required for performance advantage. Furthermore, NEP has greater flexibility as to orbit spatial orientation and, therefore, probe entry/descent conditions, and orbiter science operations are potentially more flexible because of NEP's greater capability for orbit change maneuvers compared to chemical retropropulsion. Figure 14 describes the key performance trades. With a 100 kWe NEP system, flight times from low Earth orbit to initial planet capture orbit are about 8 years for Uranus and 10 to 12 years for Neptune or Pluto missions. A one to two year reduction in flight time is possible by increasing the power level to 150 kWe or, alternatively, by eliminating the Earth escape spiral and injecting the NEP vehicle beyond escape energy by on-orbit assembled Centaur stages (a single Centuar fully fueled effects a one-year flight time reduction to Neptune while two Centaur stages allows a 2.5 year reduction).

Figure 14

FAR OUTER PLANETS ORBITER/PROBE

- PURPOSE

  COMPREHENSIVE SCIENTIFIC EXPLORATION OF URANUS, NEPTUNE AND PLUTO.

- CONCEPT

  INTEGRATED PROGRAM - 3 SEPARATE MISSIONS.
  ATMOSPHERIC PROBES AT URANUS AND NEPTUNE.
  MISSION DURATION LESS THAN 10 YEARS.
  HARDWARE COMMONALITY.

- ENABLING TECHNOLOGIES

  ADVANCED PROPULSION, AEROCAPTURE.
  HIGH RATE DATA TRANSMISSION.

- POWER USE

  ELECTRIC PROPULSION (100-200 KWE).

- NUCLEAR BENEFITS

  NEP ENABLES ALL 3 MISSIONS.
  LARGE PAYLOAD CAPABILITY.
  FLEXIBLE MISSION PLANNING.

- NUCLEAR CONCERNS

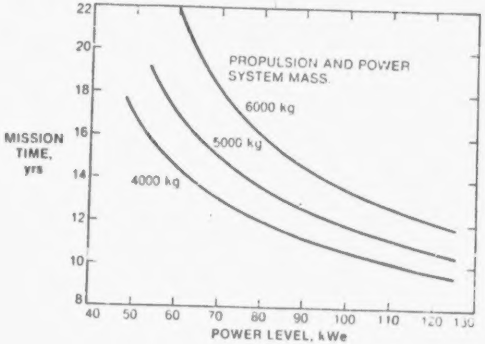
  ADEQUATE SHIELDING AGAINST RADIATION EFFECTS.

- KEY PERFORMANCE TRADE

  TRIP TIME vs POWER LEVEL.

NEPTUNE ORBITER

- SP-100 NUCLEAR POWER SOURCE
- 1500 kg (S/C AND SCIENCE) PAYLOAD
- SPIRAL CAPTURE TO TRITON FINAL ORBIT



4. SUMMARY AND CONCLUSIONS

4.1 Assessment of Civil Mission Needs

The first 25 years of the space era have provided numerous benefits to society through advancement of scientific knowledge and direct utility applications. Future expansion of civil mission goals made possible by improved capabilities and new technology developments is anticipated. The availability of abundant and economical power will be needed to spur this expansion. With this premise, the Civil Missions Advisory Group has sought to assess the objectives and requirements of such future missions, and the potential use of space nuclear reactor power systems.

A broad range of civil missions with high power requirements has been identified. These missions have objectives supported by established goals for space exploration and applications and are likely to be implemented within the next several decades. The principal areas of application are Earth and space sciences, public service communications and observational utility, and ventures in space manufacturing and resource utilization. Program development and user communities include government agencies, universities, the private business/citizen sector in the U.S., and possibly other nations as well.

The civil mission set considered to be realistic for planning purposes is comprised of more than 10 representative missions in several application classes. The first of these is a manned facility in low Earth orbit as typified by the initial space station soon to be developed, and later by growth versions which may have more specialized functions such as high-production materials processing and manufacturing. Another class of missions having direct utility to Earthbound society includes advanced, multi-function communications platforms in geosynchronous orbit and powerful radar platforms for traffic control of commercial air and sea routes. The third applications class is transport of large payloads to geosynchronous orbit and the Moon, using electrically propelled space tugs in the case of the nuclear power option. Moving away from Earth, materials processing bases may be established on the Moon and on nearby asteroids to take advantage of the potential resources residing on these bodies. Scientific exploration of the solar system, particularly orbiter/probes of the outer planet systems and sample-return from comets and asteroids, would benefit significantly from high power to drive electric propulsion systems.

Civil mission energy requirements are characterized by long-term operations (3-10 years) and nearly continuous power demand. The functional use and amount of power required varies widely across the mission set. Dominant usage categories are materials processing, electric propulsion, and communications/radar transmission. Electrical power requirements generally range from 50 to 1000 kW; a considerable number of missions would function well at the 100-200 kW level.

All of the civil mission considered in this study are enhanced to some degree by the availability of a nuclear reactor power source. In several cases the performance enhancement is very significant and possibly enabling. This assessment allows for the fact that alternative power systems (primarily solar photovoltaic and solar dynamic) or other means of mission implementation (e.g. chemical propulsion) are also available and could be employed for a number of these missions.

The primary benefits of nuclear reactor systems compared to competing energy sources are compactness, higher power density, and lower recurring cost. Demonstration of these potential advantages is underway within the SP-100 technology assessment program. Additional important benefits are independence of solar illumination conditions, simplified attitude dynamics and control for most missions, and enhanced operability in hostile environments such as the Van Allen Belts. One disadvantage or lien against these benefits is the added mass for shielding sensitive payloads from reactor radiation and heat source effects - this is especially important in the case of nearby manned operations.

4.2 Additional Issues to be Addressed in Final Report

The CMAG study is scheduled to continue through the summer of 1984. Two major items of responsiblity yet to be addressed in depth are:

1) Recommend further studies, if needed, leading to more detailed definition of civil mission requirements and power system design tradeoffs.

2) Recommend the appropriate role for NASA in the transition of space nuclear reactor technology to flight readiness.

Current activities within the SP-100 program will be appraised for purposes of forming the recommendations to appear in the final report.

The development and use of space nuclear power raises several other key issues which CMAG may choose to address in their final report. One issue is nuclear safety assurance in design, launch and operation of reactor systems. Another concern is the compatibility of military and civil needs, i.e. would reactors developed solely for defense applications be useful for civil missions?

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